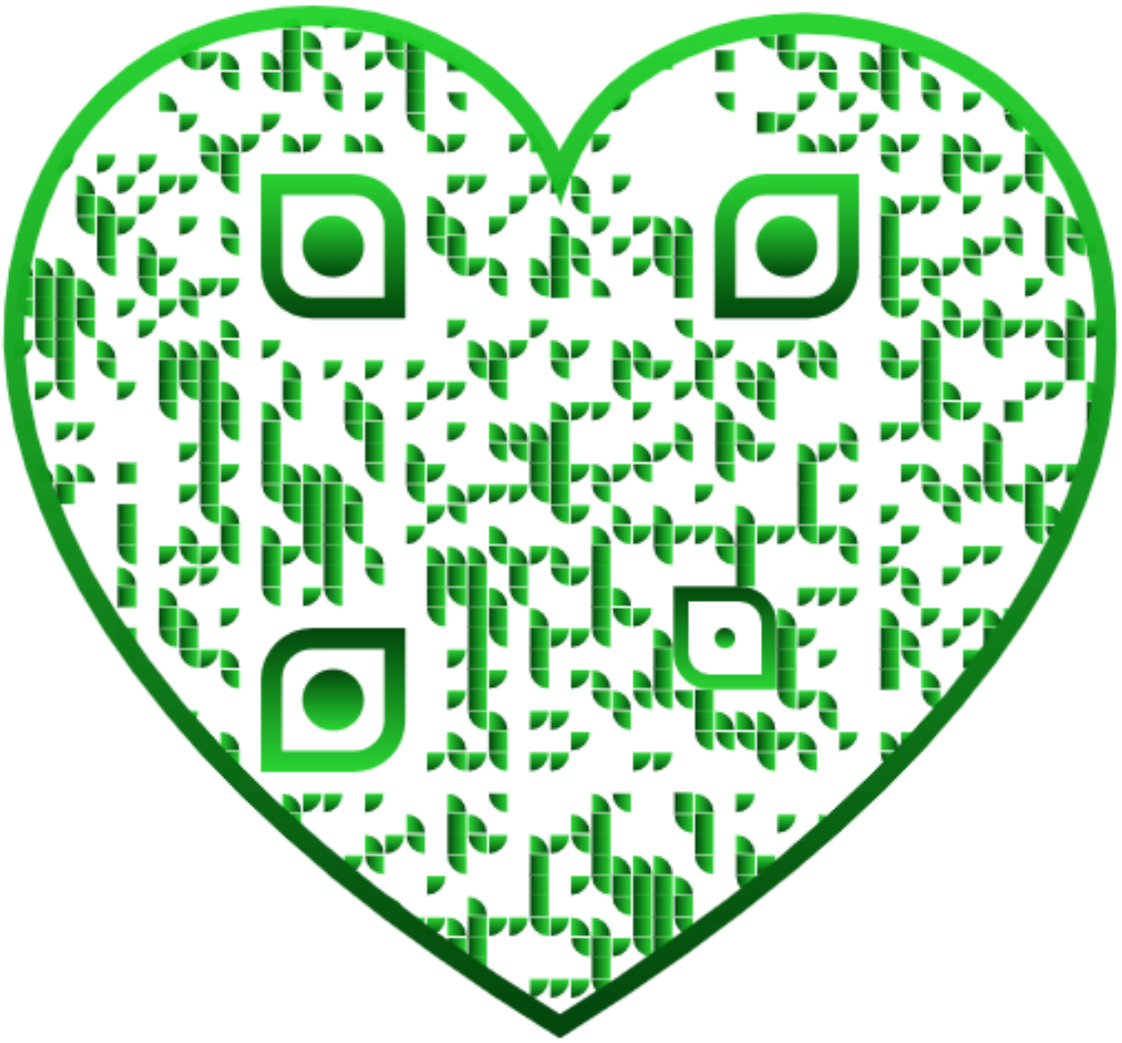
MICHAEL DENIS HIGGINS

THE SEVEN WONDERS OF THE ANCIENT WORLD

SCIENCE, ENGINEERING, & TECHNOLOGY



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SCIENCE, ENGINEERING, AND TECHNOLOGY

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Acknowledgements

The inspiration for this book came from my father's chapter on the Colossus in Clayton and Price's *The Seven Wonders of the Ancient World*. My first idea was to concentrate on the geology of the Wonders, following up on my first book, but this was widened to science in general at the suggestion of Stefan Vranka, Oxford University Press. My heartfelt thanks go to Betty Turner who read all chapters of this book many times. Stefan Vranka has given much advice and helped focus the material. Many documents came from numerous requests to interlibrary loans, UQAC, and well as the countless people who responded to my requests for pdfs. Finally, I would like to thank my wife, Judit Ozoray, for putting up with this too-long project, both in the field and at home.

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Plate 1a. The ancient Greek philosopher Plato points to the cosmos, suggesting the primordial role of mathematics, while his pupil Aristotle gestures towards the observable world, the approach favoured in this book. From "The School of Athens," 1509 CE, Raffaello Sanzio da Urbino. Public Domain.

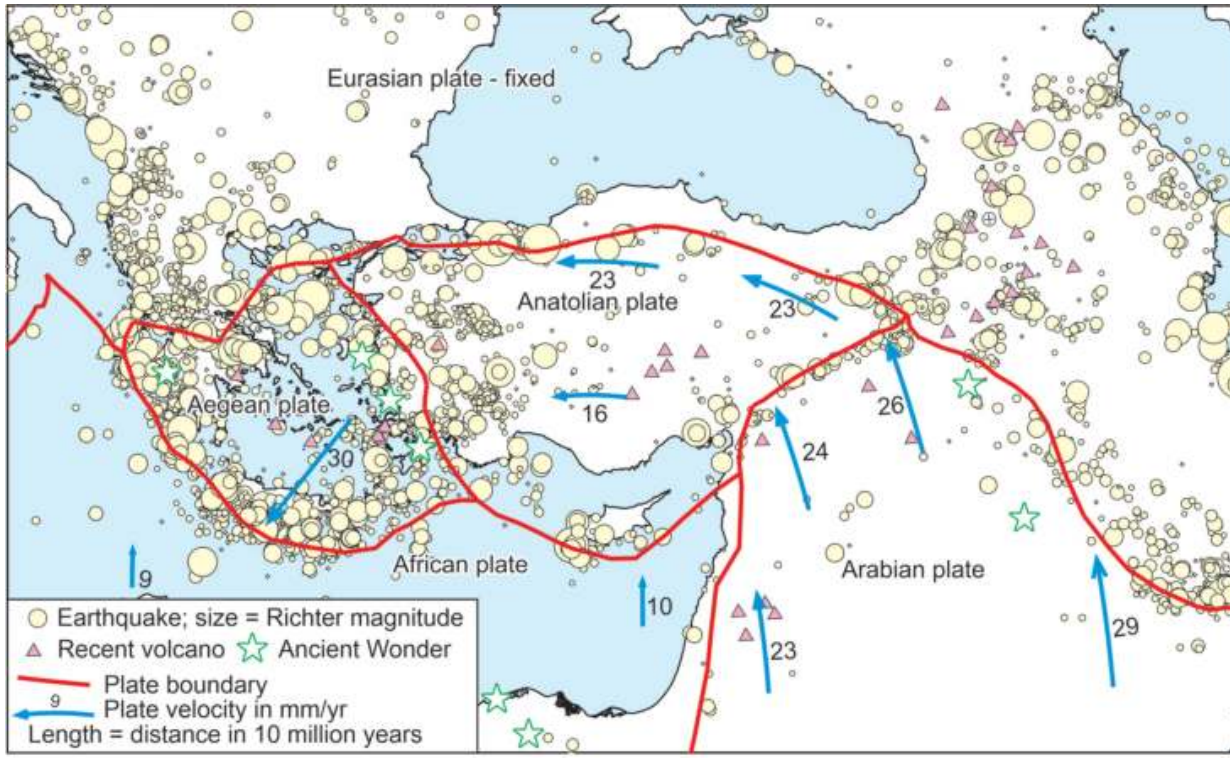

Plate 1b. Tectonic plate boundaries, earthquakes, and volcanoes of our region. Image by author after Bird, P., 2003, "An Updated Digital Model of Plate Boundaries." *Geochemistry, Geophysics, Geosystems* 4(3): 1027.

Plate 2a. Alexander the Great from a mosaic found at Pompeii dated at about 100 BCE. Public Domain.

Plate 2b. The Giza plateau after all three pyramids were finished. Image © "The Giza Project," Harvard University, with contributions by Ancient Egypt Research Associates and Dassault Systèmes.

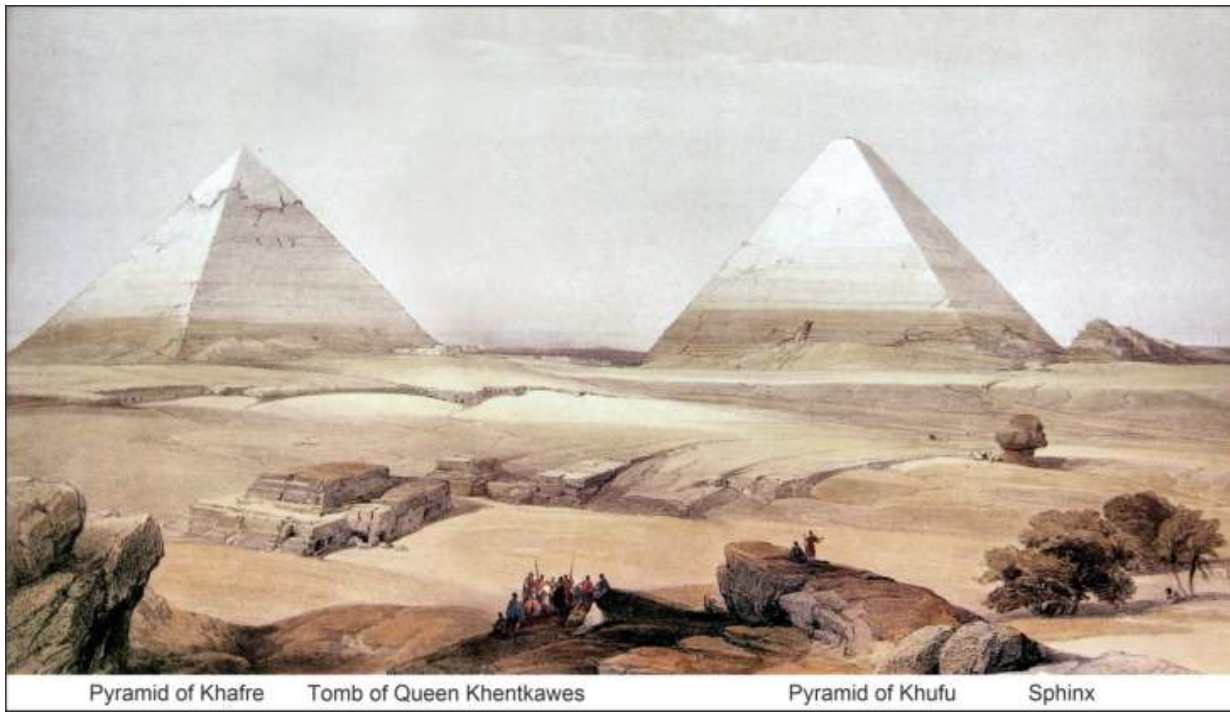

Plate 3a. David Roberts created this view in 1839 when the Giza monuments were far from Cairo and partly buried by sand. Menkaure's Pyramid is off the left of the image. Public domain.

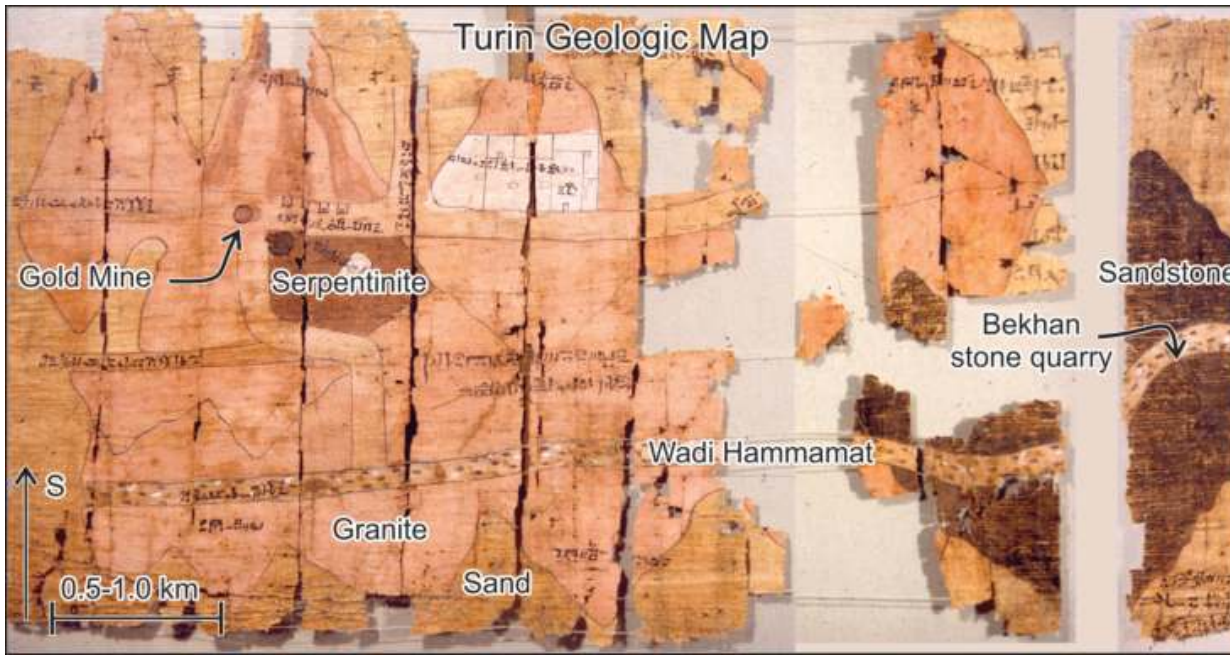

Plate 3b. The world's oldest geologic map, dating from 1150 BCE, shows part of Wadi Hammamat dry valley in the Eastern desert of Egypt, with a gold mine and quarries of the Bekhan sandstone used for statues. Image by author after public domain photo.

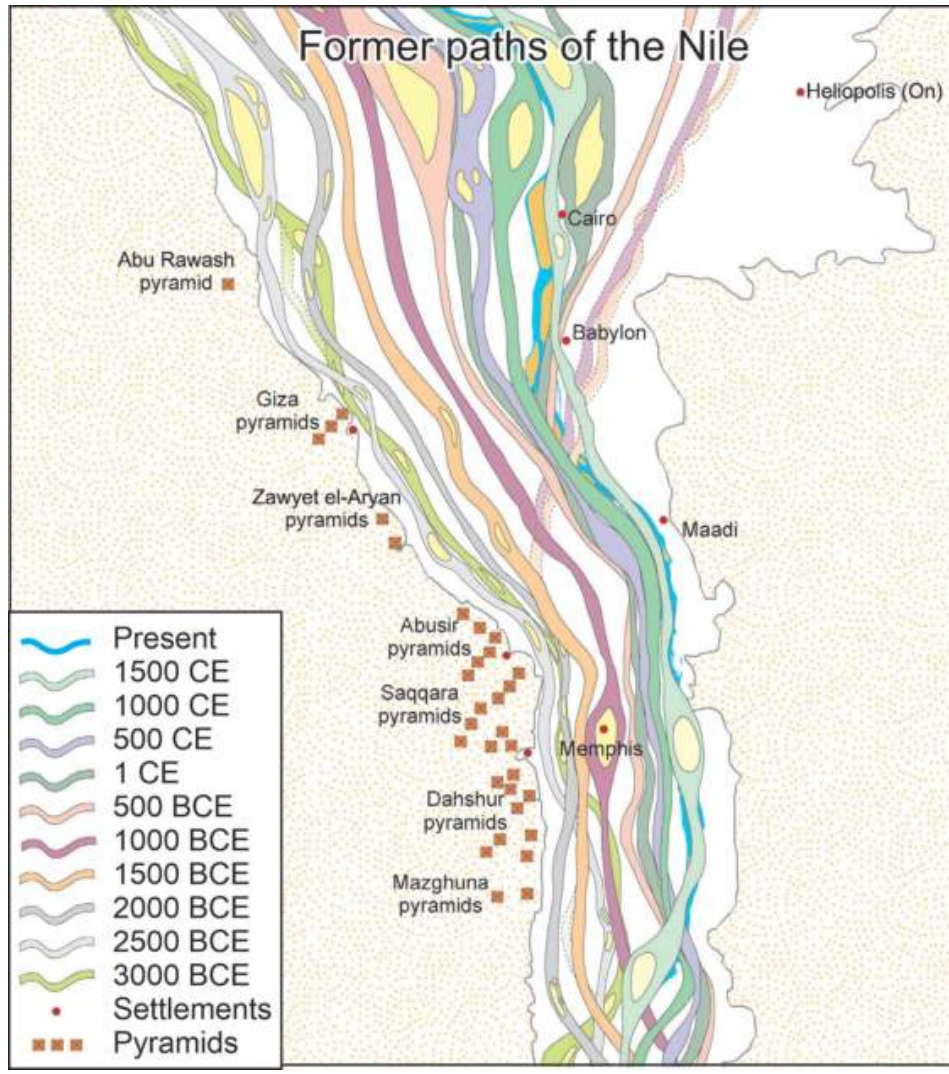

Plate 4a. The main branch of the Nile has meandered across much of the valley and was at its westernmost position when the Pyramids were constructed at Giza. Image by author after Bunbury, J., K. Lutley, and A. Graham, 2009, "Giza Geomorphological Report in Giza Plateau Mapping Project Seasons 2006–2007 Preliminary Report." Giza Occasional Papers. 3: 158–165.

Plate 4b. The Royal quarter of ancient Babylon contained the Ishtar Gate, the Processional way and the Palace of Nebuchadnezzar. The Western Outwork near the river may have enclosed the wondrous gardens. Image © Josep R. Casals.

Plate 5a. The Ishtar Gate was the most magnificent gate of Babylon and has been reconstructed in the Staatliche Museum, Berlin. The gate was faced with blue glazed baked clay bricks with rows of sirrush (dragons) and aurochs in yellow and white glazes. Photo © LBM1948 / Wikimedia commons, CC BY-SA 4.0.

Plate 5b. The walls of the Processional Way were decorated with life-size images of lions and other animals. Photo Public Domain / Wikimedia commons.

Plate 6a. Kuyunjik tell, the site of the Palace of Sennacherib at Nineveh, stood 40 metres high in 1849. Painting by Frederick Charles Cooper © Victoria and Albert Museum, London.

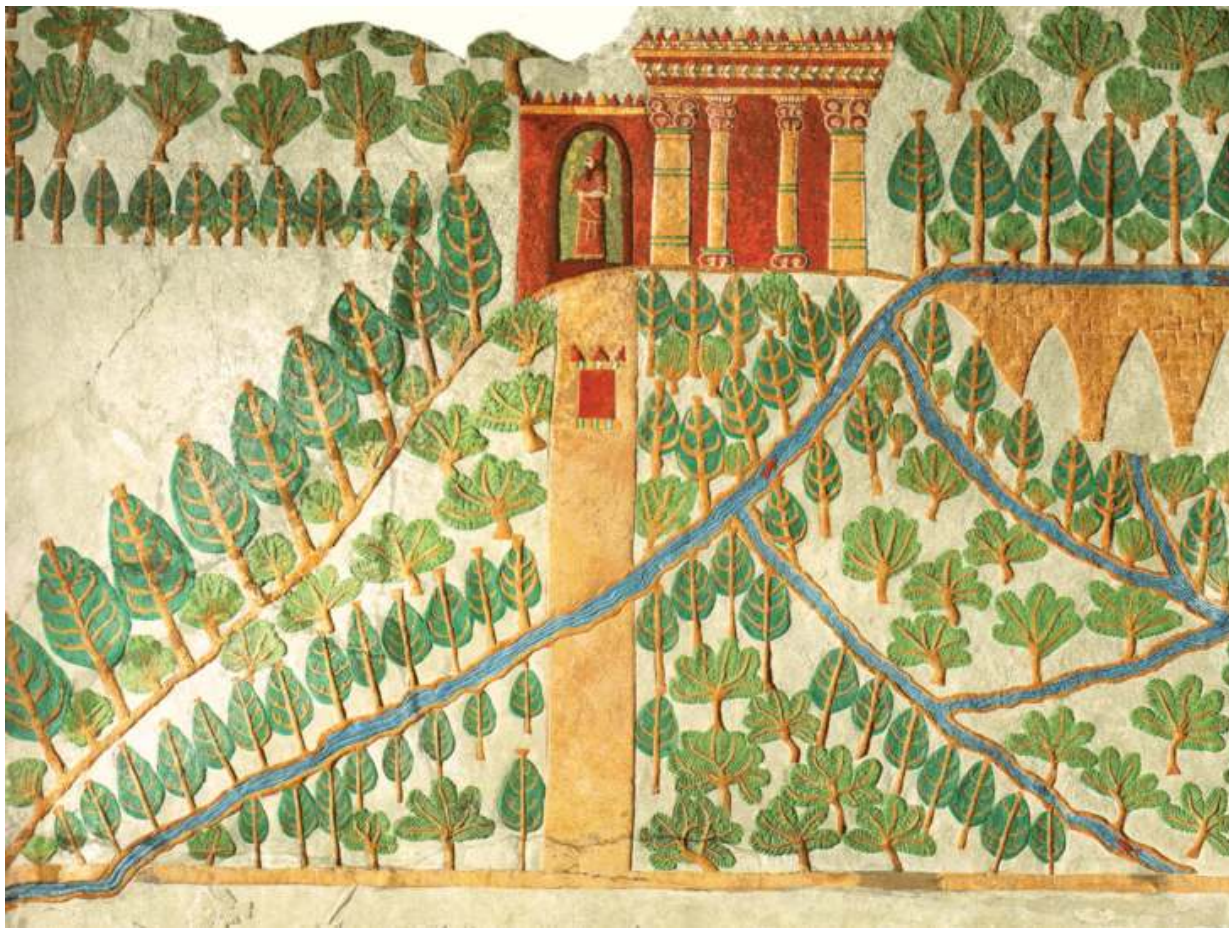

Plate 6b. A wall panel from the Palace of Ashurbanipal at Nineveh shows a terraced garden with irrigation channels. This panel was the inspiration for reconstructions of the gardens such as that shown in Figure 3-1. The image has been coloured to suggest its original appearance. Finkel, I.L. and M.J. Seymour, 2008, Babylon. Oxford University Press: Oxford; New York.

Plate 7a. Monumental statues from Assyria were loaded on rafts and floated down the Tigris to Basra, from where they were sent to Britain by ship. The head of a winged bull is visible to the right. The same transport method may have been used in antiquity. Painting by Frederick Charles Cooper © Victoria and Albert Museum, London.

Plate 7b. Natural gas flares at Baba Gurgur have been burning for at least 2,500 years. Photo public Domain / Wikimedia commons.

Plate 8a. The Sanctuary of Olympia, viewed from the west. The Temple of Zeus lies to the right. Photo © Panosgti34 / Wikimedia Commons, CC BY-SA 4.0.

Plate 8b. The Pheneos Valley is a closed basin in which rainwater normally drains through a sinkhole instead of a valley. In 1821 CE, the sinkhole was blocked and the water level in the valley rose forty metres, leaving a high-water mark on the hills that is still visible. Water that drains into the sinkhole in the Pheneos Valley travels five kilometres underground to reappear at Ladonas Spring, which then feeds the Alpheios River that flows past Olympia. Photos courtesy of the author.

Plate 9a. Looking west along the valley of the Alpheios River, this image shows that the riverbed was wide and braided in 1805. Kronos Hill is seen above the foreground figures, with the remains of the sanctuary hidden in the valley just to the left. Dodwell, E., 1821, *Views in Greece*. Rodwell and Martin, London.

Plate 9b. This specimen of quartz and metallic gold is from a vein (lode) gold deposit. Most samples have much less gold than this—typically only a few grams for each ton of quartz. Photo © James St. John / Wikimedia Commons, CC BY 2.0.

Plate 10a. The full-size reproduction of Pheidias's Athena in Nashville, USA, offers an idea of the feeling inspired by these huge sculptures. The sculptor of the statue, Alan LeQuire, stands on the base. Photo © Dean Dixon / Wikimedia Commons, CC BY-SA 4.0.

Plate 10b. The Knights of St. John decorated the entrance to their castle at Bodrum with marble friezes and sculptures taken from the Mausoleum, as seen here in 1803. These objects are now in the British Museum. Mayer, L., 1803, *Views in the Ottoman Empire, chiefly in Caramania, a part of Asia Minor hitherto unexplored*. R. Bowyer, London.

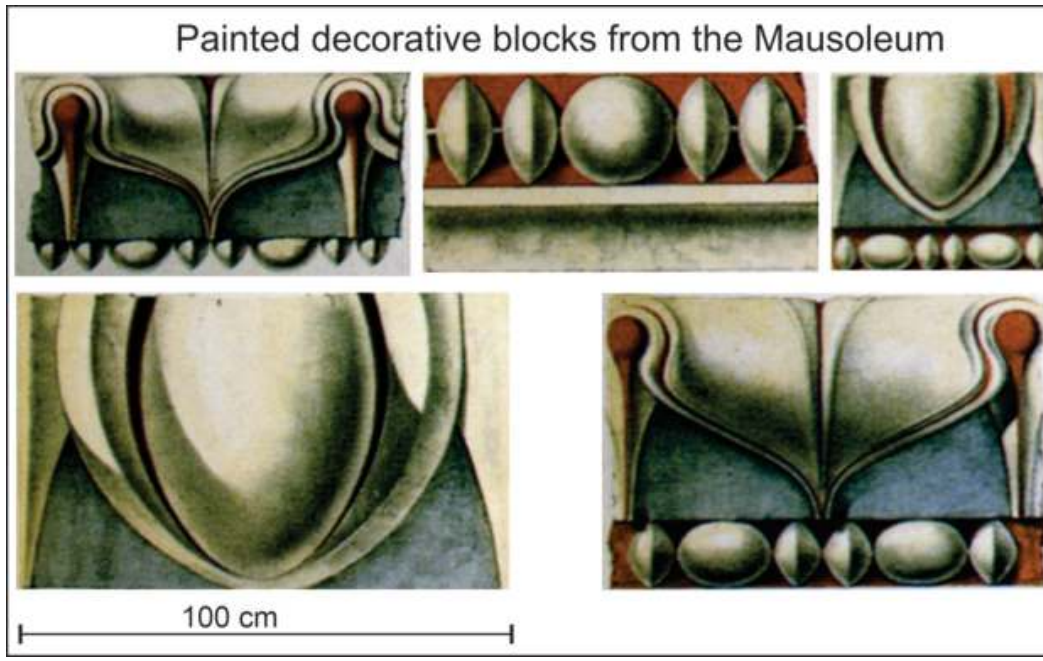

Plate 11a. Many decorative elements of the Mausoleum were highlighted with red and blue paint, as were parts of the sculptures and friezes. Image by author after Newton, C.T. and R.P. Pullan, 1862, *A History of Discoveries at Halicarnassus*, Cnidus & Branchiae. Day & Son: London.

Plate 11b. The core of the Mausoleum and the Palace walls were made of tuff blocks extracted by cutting trenches with a pickaxe. The tuff has green flattened pumice blocks and red fragments of older volcanic rocks, all set in a fine-grained pink or green matrix of volcanic ash. The dike porphyry has a similar chemical composition to the tuff but solidified directly from a magma that already had large feldspar crystals. Photos courtesy of the author.

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Photo © Austrian Archaeological Institute. OeAW-OeAI.

Plate 12b. In this view from 1836, the remains of the Şirince aqueduct lead across the valley to Seljuk hill. Image by Antonio Schranz Jr © Victoria and Albert Museum, London.

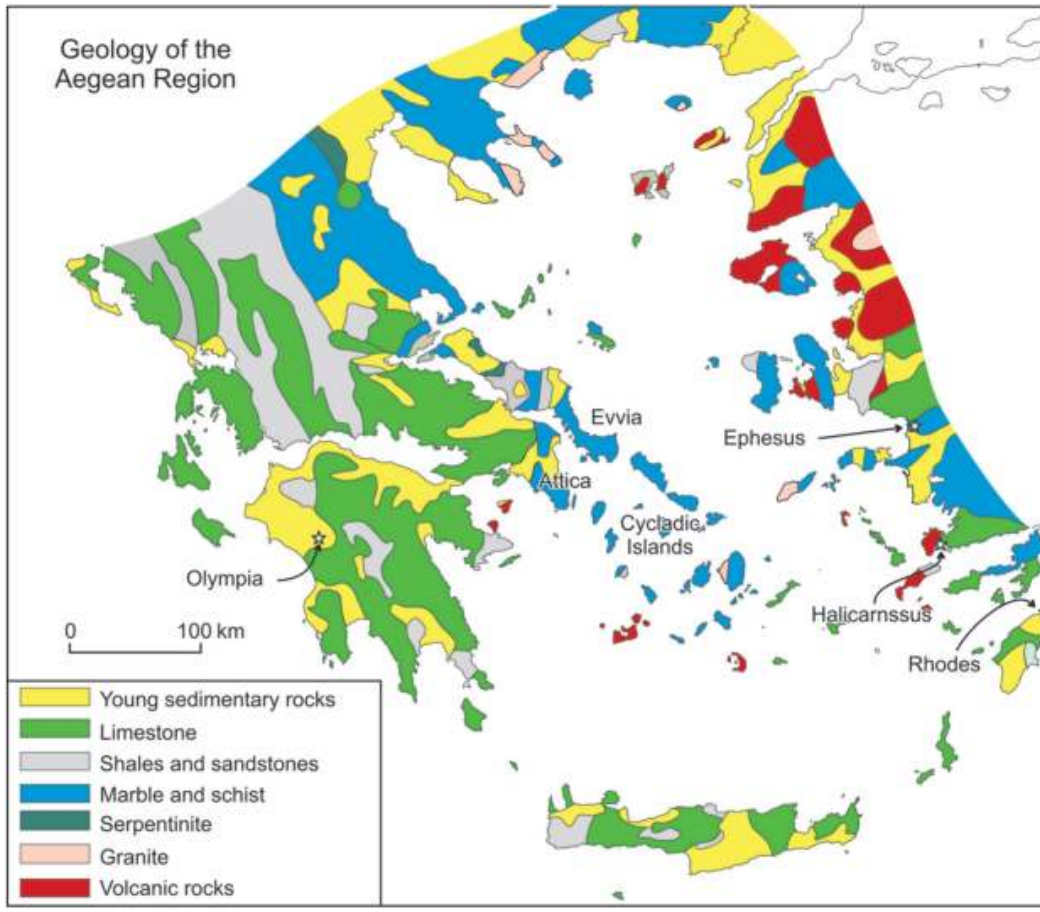


Plate 13a. The Aegean Region is rich in limestone and its metamorphic equivalent marble. Map by the author.

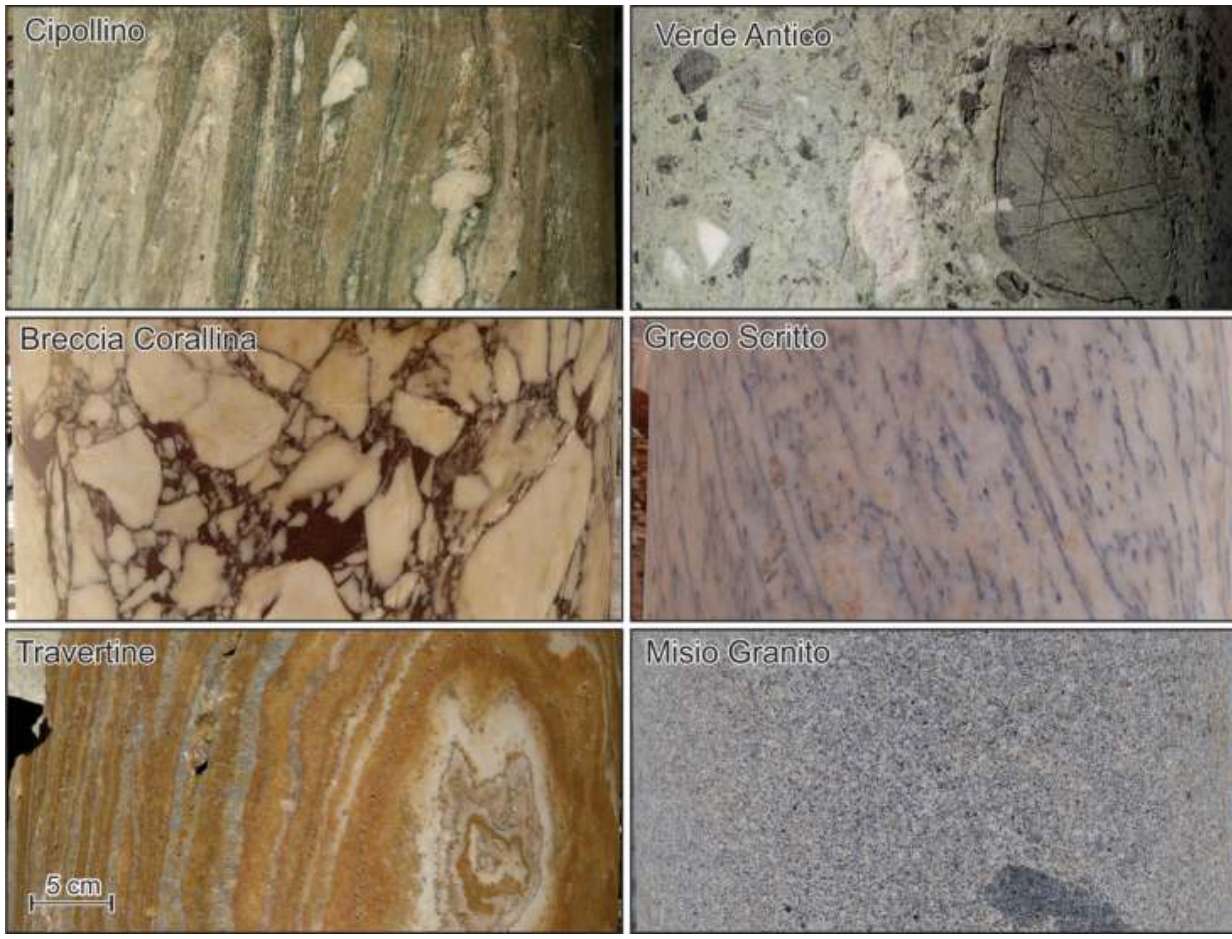


Plate 13b. Columns from Ephesus illustrating common decorative stones used there and elsewhere in the Roman Empire Photos courtesy of the author.

Plate 14a. Brightly coloured copper minerals can form near the surface by the alteration of primary sulphide ores. Green malachite was known in antiquity as *molochitis lithos* because the colour recalled mallow plant leaves. Blue azurite was known as *kuanos* from which the name of the colour cyan is derived. The brown minerals are iron oxides. Photo courtesy of the author.

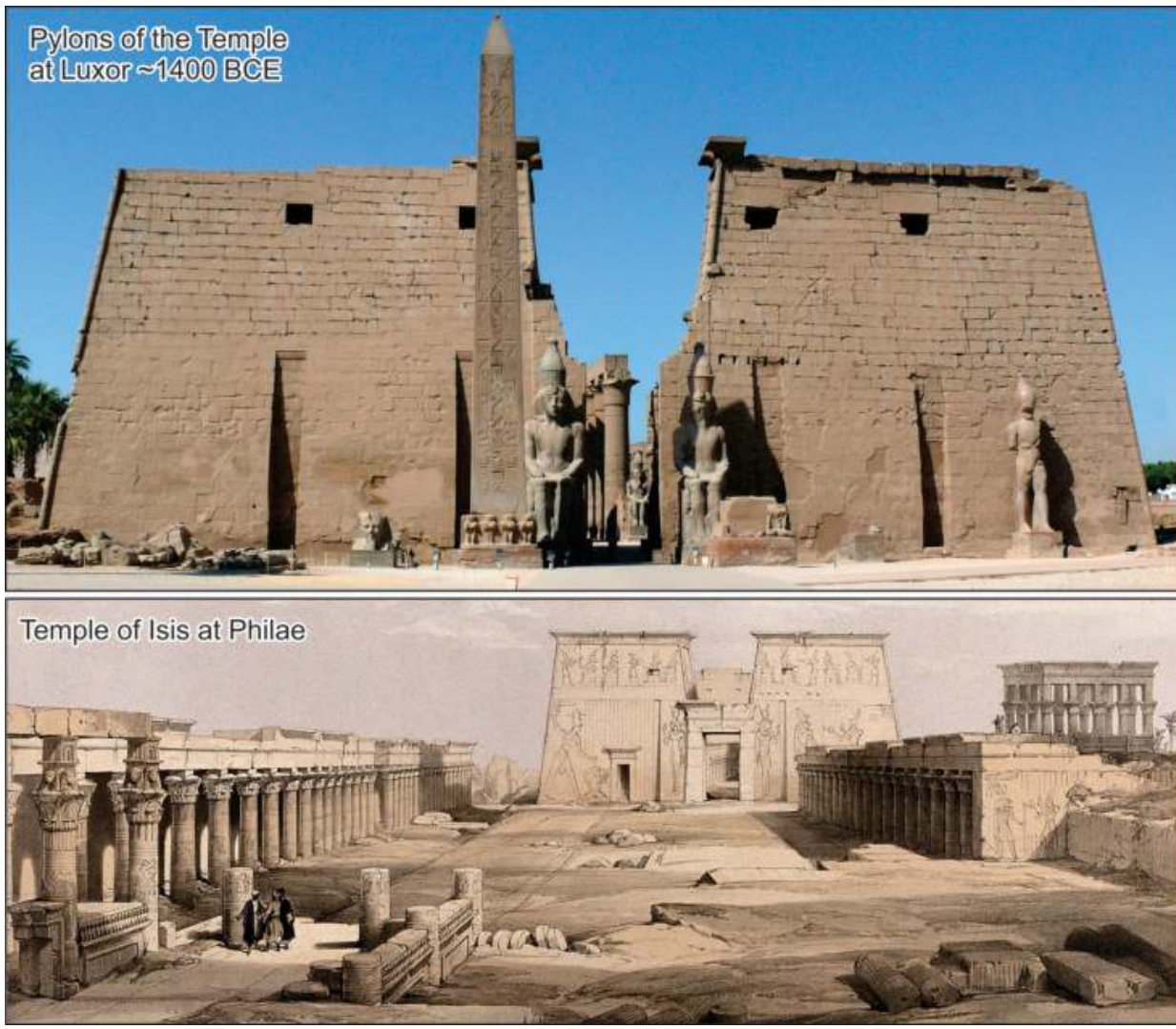


Plate 14b. The shape of the early Pharos may have been inspired by the pylons, monumental gateways, of Egyptian temples such as at Luxor. Similar pylons decorated many Ptolemaic temples, such as that of Isis at Philae. Photo © Ad Meskens / Wikimedia Commons; Image: David Roberts, 1846, Wellcome Collection.

Plate 15a. Left jamb of the monumental doorframe of the Pharos. Photo © Ellie Ga.

Plate 15b. In this Byzantine mosaic from the Basilica in Venice dating from 1270 CE, Saint Mark is shown on his way to Alexandria, symbolized by the Pharos, here in its Islamic reconstruction with a domed mosque at the top. Photo public domain.

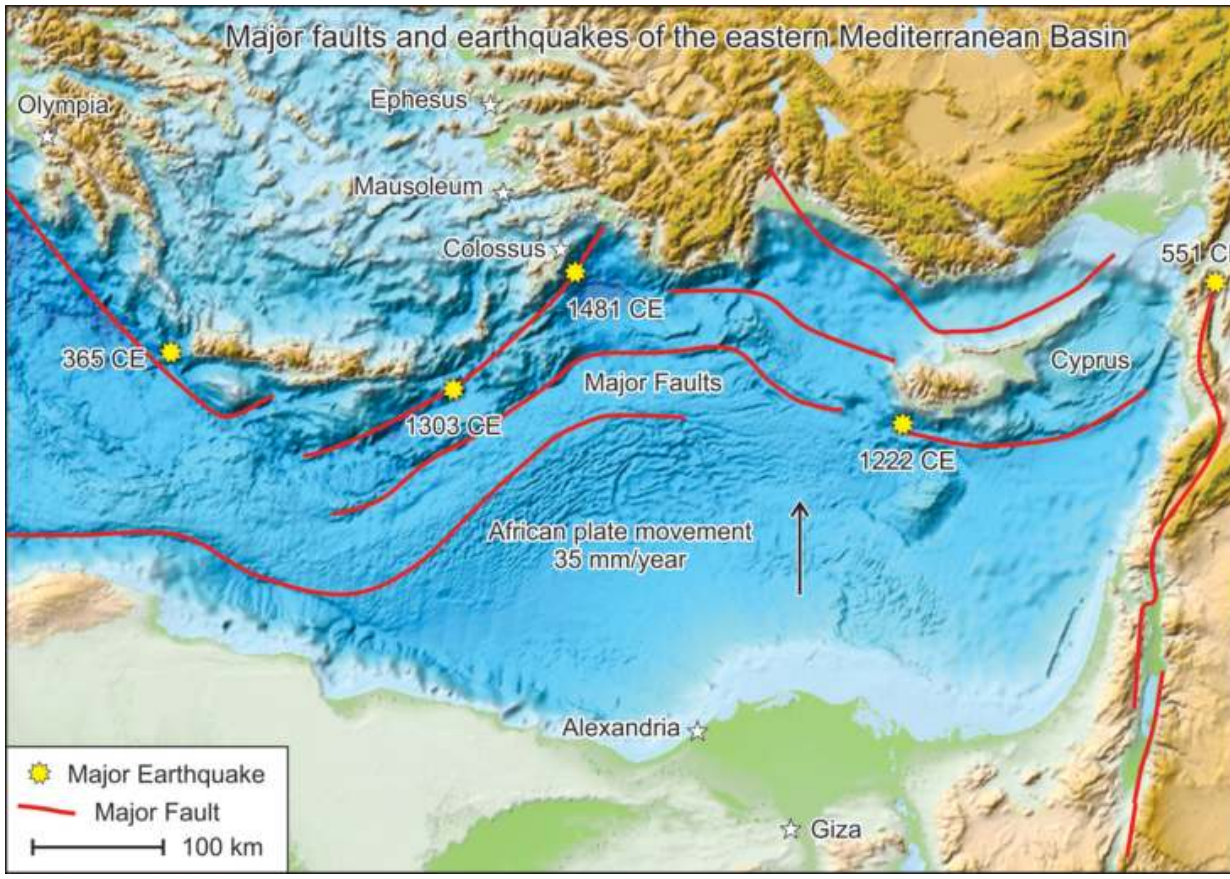


Plate 16a. The African plate is moving northwards with respect to Eurasia. Crustal shortening occurs along a series of faults that plunge northwards under Greece and Turkey, producing major earthquakes whose effects may be felt throughout the region. Map by author after Hamouda, A., 2010, "Worst Scenarios of Tsunami Effects along the Mediterranean Coast of Egypt." *Marine Geophysical Research* 31(3): 197–214.

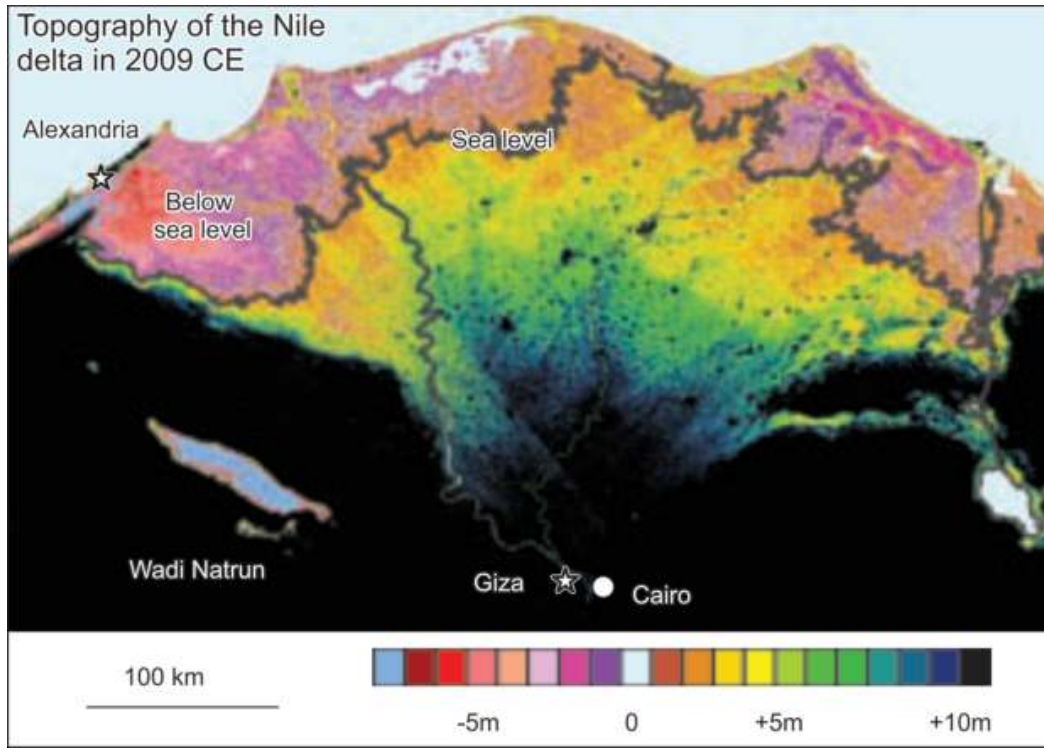


Plate 16b. Much of the northern part of the Nile Delta is now below sea level and must be pumped to keep it dry. This problem will get worse as sea level rises and the delta subsides. Image by author after Syvitski, J.P.M. et al., 2009, "Sinking Deltas Due to Human Activities." *Nature Geoscience* 2(10): 681–686.

I

Introduction

Culture and Science

I had a museum as a boy—my father was a curator at the British Museum, so I had to have my own collection. It was a bit more modest than his but included a wide range of curiosities: fossils, rocks, minerals, wool, bones, horseshoes, mosaic fragments, pottery shards, Roman lamps. As I grew older, the natural materials began to overwhelm the cultural objects, pushing me towards science and finally a career in earth science. But recently, I have reflected on what I got from that collection—an idea of the essential continuity between the natural and cultural worlds. It is that theme that I want to expand on here, anchoring the cultural end in the Seven Wonders of the Ancient World and travelling along scientific byways to try to understand more about how ancient societies used the natural environment and how they were constrained by it.

I have chosen to use the canonical list of Wonders because they are a sampling of cultural icons that appealed to ancient writers and are still hugely influential today. The early selections were variable and I could have easily added or removed items from the established group without harming my overall approach. The Parthenon at Athens or the Colosseum at Rome would have been suitable additions, and I could have removed the Gardens in Mesopotamia as they are so remote from the Mediterranean but I think there would be objections

if I omitted the Pyramids, even if they are so much older than the other Wonders.

The Seven Wonders of the Ancient World

> "Everyone knows of the renowned Seven Wonders of the World, but few have set eyes on them, for to do so you have to arrange a long journey to the land of the Persians on the far side of the Euphrates [the Gardens and Walls of Babylon]; you have to visit Egypt [the Pyramids of Giza]; you must then change direction and go to Elis in Greece [the Statue of Zeus at Olympia]. Then, you must see Halicarnassus, a city-state in Caria [the Mausoleum], and Ephesus in Ionia [the Temple of Artemis], and you have to sail to Rhodes [the Colossus], so that being exhausted by lengthy wanderings over the Earth's surface, and growing tired from the effort of these journeys, you finally fulfil your heart's desire only when life is ebbing away, leaving you weak through the weight of years."

This is how Philo of Byzantium thought of the Wonders: as sights or perhaps a "bucket" list of places to see before you die (Figure 1-1). Indeed, early compilations used the Greek word *theamata*, meaning "things to be seen," but this was later changed to *thaumata*, "wonders."[1] A list of must-see sights for tourists may seem like a modern idea that is echoed in countless travel guides but non-essential travel has a long history.[2] It may have started as pilgrimages to religious festivals along the Nile as early as 1500 BCE. In the Aegean world, voyages were mostly by sea and developed later as they were at the mercy of pirates. However, by Roman times tourism was well established throughout the Mediterranean world and our earliest surviving travel guide dates from the 2nd century CE. Pausanias's main interest was in the religious monuments of Greece, but he included many other details about legends and myths.[3]

Philo's list may not seem quite right: he included the gigantic Walls of Babylon, but omitted the Pharos, maybe because he saw

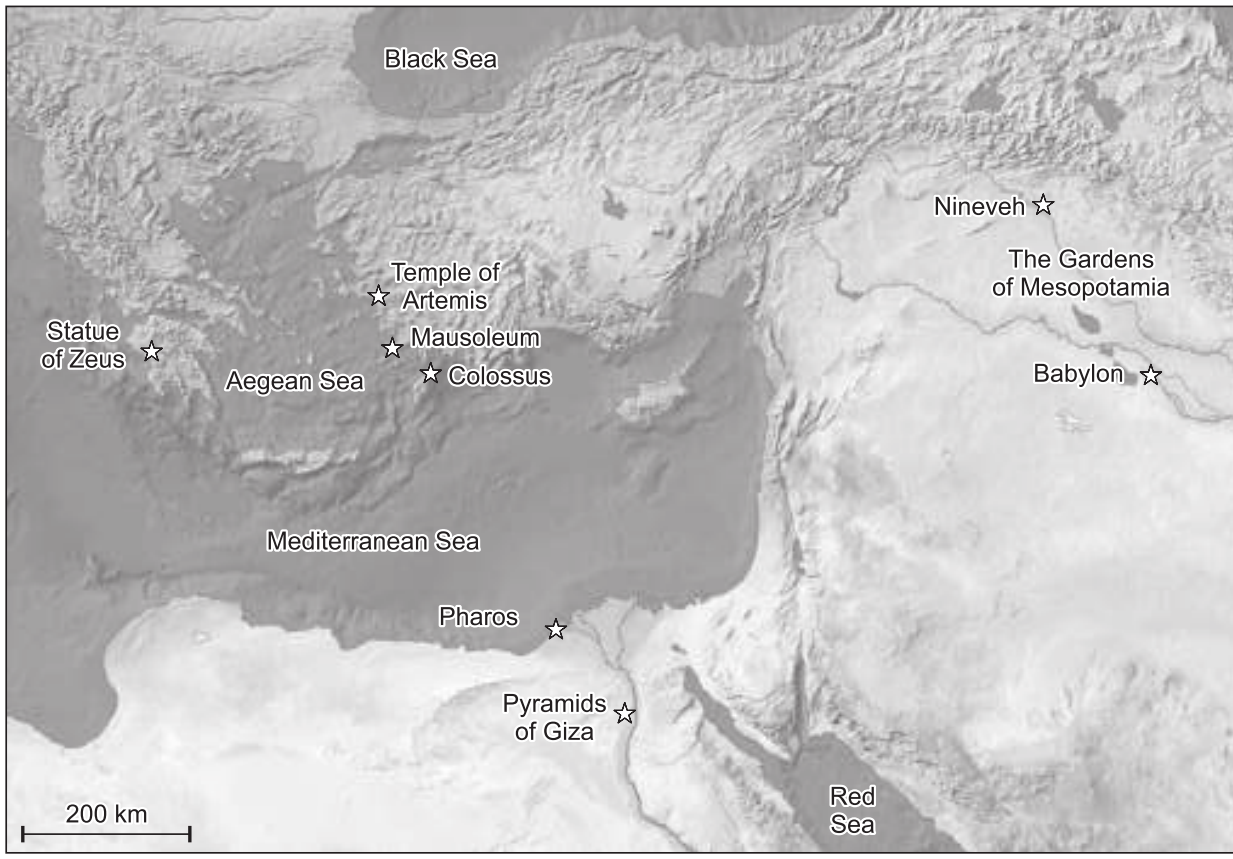


Figure 1-1: Most of the Seven Wonders were on or close to the Eastern Mediterranean Sea, except for the Gardens in Mesopotamia. Their diverse geographical settings are shown by the landscape, here revealed by the topography of the land and sea. Image created by the author after map by © Flappiefh / Wikimedia commons, CC BY-SA 4.0.

it only as a local attraction, having left Byzantium as a young man to live in its shadow at Alexandria, or perhaps because it stood out from the other Wonders by its practical purpose. In this book, I'll use the familiar list, which probably dates from the European Renaissance.

Many people have tried to discover a theme that links the Seven Wonders.[1,4] Some have suggested that they were initially part of a longer list of wonders from Alexander the Great's empire and its successor kingdoms (see box 1-1: Alexander the Great and the Wonders). But it seems more likely that the Ancient Wonders were chosen for their exceptional beauty and size, as well as the engineering challenges that they represented: the Temple of Artemis at Ephesus was the largest in the Greek world; the Mausoleum, the largest tomb in the

Box 1-1 Alexander the Great and the Wonders

Alexander III of Macedon, later known as "the Great" by those that he had not subjugated,[20] was connected to the Ancient Wonders of the canonical list (Plate 2a). In 334 BCE, he set off eastwards from Macedonia to defeat the Persian Empire, a project started by his father Phillip II. His first victory was at Granicus in north-west Turkey, and from there he went south to Ephesus, where he granted autonomy to the city. The Ephesians politely refused his offer to finish the *Temple of Artemis* with the comment "A god cannot build a temple for another god." His next stop was the city of Halicarnassus, where he besieged the strong walls over which the *Mausoleum* loomed. After that, all the cities of the region soon capitulated, including Rhodes. Forty years later the *Colossus* was erected, perhaps to commemorate his brief, but remote, rule: its sculptor, Chares, trained with Lysippus, Alexander's official sculptor. In 332 BCE, Alexander was in Egypt at Memphis, close to the *Pyramids* of Giza. From there he went to the coast to found Alexandria, where the *Pharos* would be constructed forty years later during the reign of his successor Ptolemy I. Alexander continued to Mesopotamia, where he won a battle near *Nineveh* and then proceeded to *Babylon*: both of these cities were associated with royal gardens, although the wondrous Hanging Gardens were long gone. He continued further eastward to the Indus valley, returning to Babylon in 324 BCE, where he died in the Palace of Nebuchadnezzar II, aged thirty-two. Ptolemy I took his body to Memphis and then Alexandria, where he was buried in a magnificent tomb across the harbour from the Pharos.

There was also a connection to the *Sanctuary of Olympia*, even though Alexander never visited the place. An unfinished monument to his father Phillip was completed there on Alexander's orders and filled with statues of himself and his family.

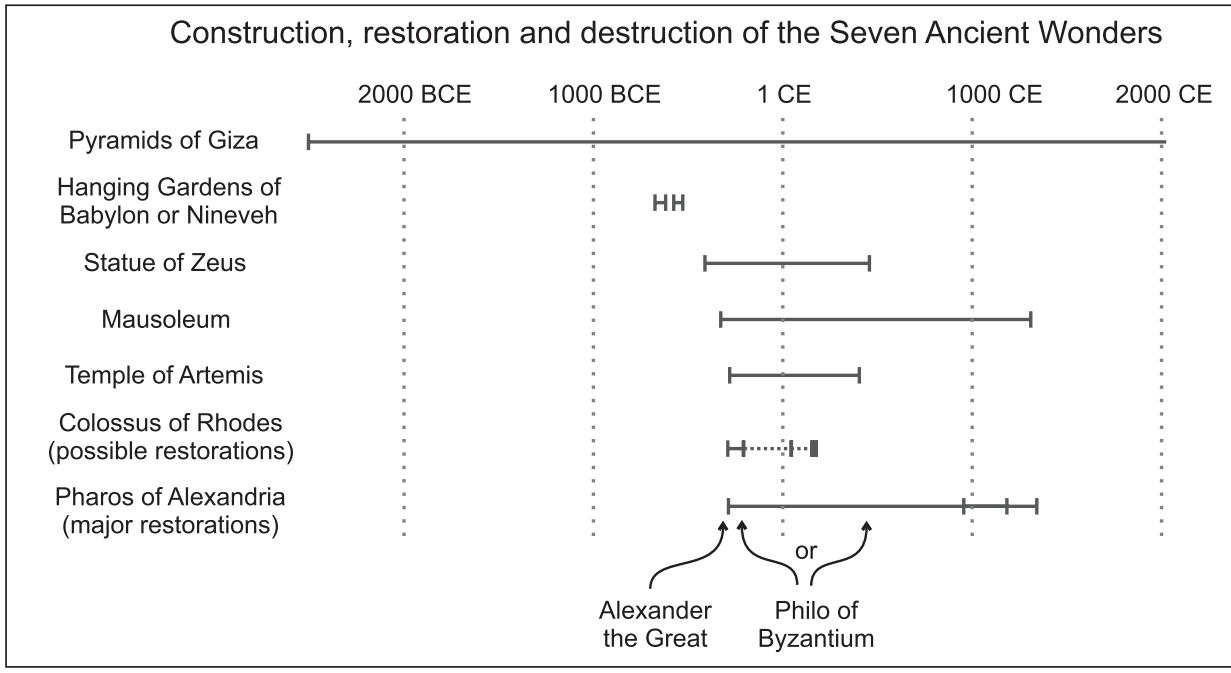


Figure 1-2: Timelines of the Ancient Wonders. Dates BCE (Before Common Era) are numerically equal to BC and dates CE (Common Era) are equivalent to AD. Image by the author.

Aegean; the Colossus, the largest bronze statue; the Zeus at Olympia, the largest statue of gold and ivory; and the Pharos, the tallest building. We know little of the Hanging Gardens, but they clearly impressed people. The Pyramids of Giza speak for themselves as they alone survive and continue to amaze travellers.

Philo speaks as if all the Wonders were extant during his lifetime, but that was not so (Figure 1-2). Although traces of the Walls of Babylon still existed, the Hanging Gardens did not, as they had a short life, perhaps that of a single ruler, long before Philo. However, subsequent rulers in Mesopotamia may have had similar gardens that were conflated into a single Wonder. The Colossus is generally thought to have fallen shortly after construction but may have been reconstructed several times, as I'll show later. So, Philo's journey would have been to five intact Wonders, all reasonably accessible from the Mediterranean Sea, and a difficult overland journey to see the traces, or rumours, of the remaining two. Despite the passage of time, a modern traveller could follow the same overall route but with different challenges.

Although one of the Wonders has survived more or less complete, the sorry state of the others means that they are now more symbols than artefacts, but powerful nevertheless. Their images are part of our culture and their names have been incorporated into our language, particularly the Mausoleum, Colossus, and Pharos. The notion of the Ancient Wonders has inspired endless sevenfold lists, whose lifespan is likely to be much less than that enjoyed by those of the Ancient World.[4]

To understand how the Wonders were constructed, we must start with the works of ancient writers and complement this with information from archaeological excavations. Many people wrote about the Seven Ancient Wonders, but most of their texts survive only as fragments recycled in later works or even just titles in catalogues. In some ways, these works resemble traces of ancient life preserved so fragmentarily in fossils or older genetic material found in descendant organisms.

One of the most comprehensive works is that ascribed to Philo of Byzantium, quoted earlier. We don't really know when his "*De Septem Mundi Miraculis*" was written or even really by whom.[5] Philo of Byzantium was an engineer writing in the 3rd century BCE, but the style of this manuscript is rather different from his other works, and it may have been written much later, perhaps from notes by Philo[5] or by someone else as late as the 6th century CE.[6] Whoever the author, whenever it was written, all that exists today is a single copy made in the 9th century CE, unfortunately not intact: parts on the Temple of Artemis are missing as well as the entire section on the Mausoleum.

Now that I've chosen my cultural icons, I want to examine aspects of ancient and modern science that are pertinent to the Wonders. In this book, I use the word science in its widest sense to include science as pure knowledge, engineering as the practical application of knowledge, and technology as the realization of engineering practice. The fragments of ancient science that have been passed down to us can reveal how the Wonders were put together, and modern science

can help fill the gaps in our knowledge and show how environmental changes affected the course of history.

Ancient Science in the Mediterranean Region

Much early science was founded on some aspects of practical knowledge.[7] For example, Hesiod (~700 BCE) wrote about chronology—specifically the seasonal appearance of the stars and phases of the moon as a guide to agricultural activities. Medicine gives us another example of the application of practical knowledge to human activities. However, wide fields of practical work, what we would call technology, were little discussed, probably because they were dirty and dangerous and hence the domain of slaves or lower-class freemen. Unfortunately, this includes many subjects of particular importance to the Wonders, such as stone and metalwork: there are many more images of artisans making metal objects as compared to such low-prestige activities as mining or smelting and few descriptions of any of these activities.

Early science and engineering changed slowly compared to today, and one factor may have been related to the availability of energy and resources.[8] We now rely largely on chemical and electrical energy to power our technology, but in antiquity there was another source: slaves. Slavery was so well integrated into society that most people at the time could not imagine civilization without it. Slavery may not have been an ethical or efficient power resource, but its availability may have stifled innovation in that the easiest solution to most problems was just to use more slaves. This may be why steam power and possibly chemical batteries were known in antiquity but were regarded as toys or religious items.

The 7th century BCE saw the development of natural philosophy, the precursor of modern science. At first, this was not an exploration of practical knowledge but more an intellectual exercise into

the question of how our ordered world came into being, a subject now covered by the term "cosmology." Early ideas were based on the fundamental roles of water, air, fire, and earth, alone or in some combination. Pythagoras and Plato proposed that mathematics underlies the order of the cosmos, a theme that has come to dominate modern science (Plate 1a). However, it was Aristotle who launched the idea of evidence-based enquiry, which we know as the scientific method.

In the early 3rd century BCE, the centre of learning of the Mediterranean world passed from Athens to Alexandria when Ptolemy I built the great library and funded its residential college. Many scientists, mathematicians, and writers worked here, including Philo of Byzantium whom I mentioned above. They were from all over the region but their common language was Greek. The institute had its ups and downs but existed until the late 4th century CE when an edict from the emperor ordered the destruction of pagan temples, including the Temple of Serapis, which may have contained the last remaining scrolls. Although women may have studied in Alexandria, we know little about them except for Hypatia, who was active just after the destruction of the library. Her "scientific salon" may have been a meeting point for the surviving science refugees from the library. Although the library produced much knowledge, the scholars appear to have valued literature and pure science, with less interest in engineering and technology.

Although science and particularly engineering continued to advance in the Hellenistic Period and Roman Empire, the Seven Wonders were already built so these innovations are of lesser interest to us.[9] However, explanations of natural phenomena and technology at this time can certainly inform us about science in earlier periods. Of particular importance is Pliny the Elder, who wrote an encyclopedia of natural history that has survived intact. I would now like to jump to modern scientific methods, which we can use to understand ancient science and environments, especially as they pertain to the Wonders.

Modern Science

Modern science started to develop about four hundred years ago following the confluence of several factors. The most important was probably the development of printing, which enabled the rapid and widespread dissemination of knowledge, as well as its preservation from decay, fire, or religious fervour. Since that time the pace of science has increased exponentially, partly due to the increasing number of participants as well as the ease of access to information.

Much of modern science can be broadly divided into the experimental sciences of physics, chemistry, and parts of biology; and the historical sciences of astronomy, earth science, palaeontology, and archaeology. In the former, natural systems are commonly simplified so that they can be replicated in the laboratory; in the latter, the experiment or event has been completed and we have to interpret the process from the results. The historical sciences rely on a knowledge of the timing of events, hence the emphasis on chronology (see box 1-2: Scientific Chronology). Of course, this experimental/historical division is not rigid but just a description of the dominant approach used in different subjects.

In this book, I want to use science to increase our understanding of the Wonders, such as their context, the materials used in their construction, and the forces that led to their damage or destruction. Another theme is the application of science to the understanding of ancient technology, very little of which was recorded. Few of the ancient workers could read or write, and it was not necessary to record their actions because it was passed on orally to other workers, commonly their children. Indeed, such information may have been *trade secrets* that were conserved within the profession.

Much of the modern science that can be applied to the understanding of the Seven Wonders is fundamentally interdisciplinary. Pure physics is not easily applicable, but geophysics can be used to examine the interior of the Pyramids. Similarly, chemistry is represented by the

Box 1-2 Scientific Chronology

Many events, such as the creation of an object or the formation of a rock, can be dated using scientific methods.[21] Most methods depend on a "geological clock" that is set to zero by the event and the subsequent accumulation or loss of something that can be measured. Geologists usually make a distinction between methods for younger events, less than 50,000 years, and those for "deep time," that is up to the age of the earth, which formed some 4,500 million years ago.

Special dating methods are applied to archaeological materials like pottery.[21] For instance, nuclear particles produced by the radioactive decay of natural elements like uranium can boost the energy of electrons that may become trapped in the crystal lattice. There are several ways of releasing this energy and hence determining the age of the material. One of the best known is thermoluminescence, which is based on the emission of light when a sample is heated. Other methods can release the trapped energy using light or can measure directly the energy of the electrons in place.

Carbon-14 is a method for dating "young" plant material, animal remains, and some cave deposits. It is based on the decay of a radioactive isotope of carbon that is formed continually in the upper atmosphere and incorporated into plants by photosynthesis. Recently, accuracy has been improved by calibration against wood samples dated independently by counting tree rings.

Igneous and metamorphic rocks, like marble, lava, and granite, are dated using radioactive isotopes that were created just before the formation of the solar system, such as uranium and potassium. Most sedimentary rocks like limestone cannot be dated exactly using these methods, and the presence of specific fossils are used instead to correlate these rocks to ones of the same age that have been dated from volcanic rocks fortuitously included in the sequence.

composition of natural materials, geochemistry, as well as anthropogenic materials like metal ingots or ceramics. One of the recurring themes is the influence of earth science, viewed in its widest possible sense, on our understanding of the Wonders.

Earth science examines our planet at all scales: from the whole globe to the atomic structure of minerals. There are many subdivisions, such as those that deal with the solid part, geophysics, geochemistry, and geoarchaeology;[10] and those concerned with the fluid part, for example, hydrogeology and palaeoclimatology[11] (see box 1-3: Getting Information on Ancient Climates).

The vast range of landforms and rocks on earth initially meant that we did not have a clear vision of the large-scale functioning of our planet, but this changed with the development of the theory of Plate Tectonics in the 1970s, enabling us to link deep earth processes with surface observations. This theory proposes that the earth is covered with a generally rigid shell about 150 kilometres thick, which "floats" on a hotter and weaker interior. This shell is composed of about fourteen large plates, and many smaller ones, each of which moves independently from its neighbours (Plate 1b).[12] Geological activity, such as earthquakes, volcanoes, and mountain building occur more frequently along plate boundaries. Four or five of the Wonders were built close to these places.

Earth science is linked inextricably and inevitably with culture and civilization: even the other name of the discipline, geology, links *gē*, the earth, with *logos*, knowledge and culture. Earth processes shaped the conditions that gave rise to the advanced social organization and wealth required for the construction of the Seven Wonders.[13] Climate, water, and soils—all partly controlled by these same earth processes—determined agricultural productivity, which in turn, sustained populations large enough to provide the labour and wealth over and above immediate survival needs. Earth processes provided the resources needed for construction: stone, metals, water, and other materials. The adage "If you can't grow it, you have to mine it" comes to mind.

Box 1-3 Getting Information on Ancient Climates

Climatic changes may have had a strong impact on many ancient cultures, including those that produced at least three of the Ancient Wonders, so how do we find out about past climates?[11] First, the difference between weather and climate: climate is weather averaged over many years and for a large region. For example, a storm that causes a flood is weather, but the frequency of such events is climate. Ideally, we would like to know as much about ancient climates as we know about the weather today, but that is not possible—the best we can usually get is a record of mean temperatures and rainfall. We can get both global and local information on past climates from continuous natural records. There are many ways that we can use to investigate ancient climates and I'll only mention the most important.

One of these records, for the last few million years, come from microscopic fossils preserved at the bottom of the oceans and sampled in deep-sea cores. These organisms lived at the surface and preserve a record of the isotopic composition of seawater at that time, which can tell us about the amount of glacial ice on land and hence the global sea level and temperature (see box 6-6: Sea Level and Cultural Developments).

Ice cores from glaciers give records of the atmospheric conditions during the last few hundred thousand years. It may seem contra-intuitive, but there is a connection between the extreme climate of these places and that elsewhere on the planet. The deposition temperature of the ice is recorded by the isotopic composition of hydrogen and oxygen in the ice, and air bubbles caught in the ice give us samples of the atmosphere, including its carbon dioxide content. Atmospheric pollution, such as lead from smelting during Roman times, is also preserved in the ice. Finally, layers of volcanic ash can bear witness to major eruptions, such as that of Thera, Greece, in ~1600 BCE.

Limestone deposits in caves, such as stalagmites, stalactites, and flowstones, can tell us about local climates (see Chapter 3: Water Supply). Rain or snow falls on the surface and percolates downwards

dissolving carbonate minerals from limestone or marble. When the water reaches a cave, carbon dioxide is lost to the atmosphere provoking crystallization of carbonate minerals. If there is an important seasonality of rainfall, then a distinct layer will form each year. The age of these layers can be determined by counting for young deposits still in place and by using isotopic methods like carbon-14 or uranium-series for older or collapsed material. The width of layers can tell us about the amount of rainfall in that year, and their isotopic composition can provide the average atmospheric temperature.

Recent climate information can be derived from wood. Many species of trees lay down annual rings and their width can tell us about the rainfall in that year. The isotopic composition of the wood can tell us about the temperature. We can extend the record further by matching tree-ring width sequences from living trees to dead trees or cut lumber.

Finally, construction was financed in some cases by trade, which was facilitated or hindered by regional geography.

The American historian Will Durant said that "Civilization exists by geological consent, subject to change without notice,"[14] to which recent experiences suggest that we should add "biological consent": the Wonders were not immune to either force. Earthquakes, aided and abetted by other processes, both natural and human, often took a lead role in their demise. Ironically, geological processes also helped protect the remains of some Wonders, by burying them and thus reducing the opportunity for plunder by later peoples. All these things happened long before our lives and I'd like to return to the theme of time.

Earth science gives us a view into the unimaginably distant past, where the unit is commonly a million years. This necessitates a world view that has been called *Timefulness* by Marcia Bjornerund.[15] She comments that "A recurrent theme [in earth history] is that long periods of planetary stability have ended abruptly . . . when rates of environmental change outpaced the biosphere's capacity to adapt." I think

that this idea can be extended to our human timescale—societies can be stable for long periods, but this ends when they are unable to adjust sufficiently fast to environmental changes. The downfall of such civilizations was not necessarily brought on directly by events like rapid climate changes, pandemics, or earthquakes but may have been mediated by invasions of people from outside the affected region. Many aspects of the Wonders' story express such events.

Geomyths

Finally, I would like to mention that some legends, myths, and stories in ancient literature may reflect observations of events that can be interpreted as actual geological phenomena, although they may have been conflated, transposed in time, and moved in space to satisfy the requirements of a narrative.[16,17] Geomyths enter into the story of five of the Ancient Wonders.

Many such geomyths concern catastrophic events such as volcanic eruptions, earthquakes, tsunamis, fires, and floods. A popular example is the biblical story of the Exodus (13:21): "Now the Lord was going before them by day in a pillar of cloud to lead them in the way, and by night in a pillar of fire to give them light, so that they could travel day or night." This has been interpreted as a description of the 35-kilometre-high column of volcanic ash from Thera (Santorini) Volcano during a catastrophic eruption in ~1600 BCE. Similarly, the subsequent inundation of the Pharaoh's army could be interpreted as a tsunami produced by the eruption.

Less disruptive geological phenomena may have been behind other geomyths: for instance, fossil bones of mastodons and other huge animals of the Pleistocene period (2.6 million to 12 thousand years ago) are frequently found in Greece and may have inspired legends of an ancestral race of humanoid giants.[18]

However, we should be careful as to what constitutes a geomyth and exclude pre-human events that cannot be based on ancient

observations, such as the story related by Pliny the Elder concerning the two hills flanking the Gibraltar Strait—the Rock of Gibraltar and Jebel Musa. ". . . the inhabitants have called them the Pillars [Columns] of Hercules; they believe that they were dug through by him; upon which the sea, which was before excluded, gained admission, and so changed the face of nature." This legend is not a geomyth as there could not have been any human observers—the strait was breached more than five million years ago.[19] It should perhaps be considered an observation and possible poetic explanation, with nature personified as a supernatural being.

I have now set the stage for my book: the cultural icons are those chosen by the ancients for their beauty and size. Obviously, I have had to select what aspects of science, engineering, and technology I treat and have been guided by what seemed to be most important, but inevitably my personal interests have intervened. In the following chapters, I will treat the Wonders in chronological order of their construction.

2

The Pyramids of Giza

Monuments of the Giza Plateau

The three largest Pyramids of Giza are unique amongst the Seven Wonders in their awesome size and simplicity of external form that belies an inner complexity of elaborate chambers containing sarcophagus and burial goods, complemented by mortuary temples and causeways (Figure 2-1, Plate 2b). The whole ensemble represented a theme common to many of the Wonders: the link between Earth and Heaven, humans and gods, here mediated by the pharaohs.

The Pyramids have always been first on the lists of the Ancient Wonders, prominence usually given to the largest, the Pyramid of Khufu (Figure 2-1). The Great Pyramid satisfies one of the essential criteria of the Ancient Wonders—size. Indeed, it is so big that it was four thousand years before the cathedrals of Europe surpassed it in height. It is the only one of the ancient wonders to still survive in a state that would have been recognizable to the ancient list-makers.[22–24]

All three pyramids are so well preserved that we do not need the ancient descriptions on which we must rely for the other Wonders.[23] This is doubly fortunate as the oldest surviving accounts were written by the Greek historian Herodotus some two thousand years after the pyramids were completed. He and most other ancient writers were impressed by the edifices, but many were also critical of the pharaohs that had them built. Pliny the Elder expressed this well in the 1st century CE: "And it is a device of tyranny to make the subjects poor, so

Figure 2-1: The three pyramid complexes of the fourth dynasty pharaohs were built on the Giza Plateau. This image is derived from a 3D model of the plateau and monuments. Image © The Giza Project, Harvard University, with contributions by Ancient Egypt Research Associates and Dassault Systèmes.

that a guard may not be kept, and also that the people being busy with their daily affairs may not have the leisure to plot against their ruler. Instances of this are the Pyramids in Egypt."[25] We do know that the work was hard (see box 2-1: Ancient Working Conditions), even if it appears that many of the workers were not slaves.[23]

Box 2-1 Ancient Working Conditions

In a papyrus text, now called the "Satire of the Trades," a scribe recounts the hardships of manual workers and concludes that his profession is the best.[81] It is in the form of a letter from Khety to his son Pepy and was probably written around 1900 BCE, some six hundred years after the pyramids of Giza were constructed. However, Egyptian society was very conservative and hence the conditions of manual work were unlikely to have changed much. Here are some pertinent professions:

> I do not see a stoneworker on an important errand or a goldsmith in a place to which he has been sent, but I have seen a coppersmith at his work at the mouth of his furnace. His fingers were like the claws of the crocodile and he stank more than fish eggs.
>
> Every carpenter who bears the adze is wearier than a labourer. His field is his wood, his hoe is the axe. It is the night that will rescue him, for he must labour excessively in his activity. But at nighttime, he still must light his lamp.
>
> The potter is covered with earth, although his life is still among the living. He burrows in the field more than swine to bake his cooking vessels. His clothes being stiff with mud, his headcloth consists only of rags so that the air which comes forth from his burning furnace enters his nose. He operates a pestle with his feet, with which he himself is pounded, penetrating the courtyard of every house and driving earth into every open place.
>
> I shall also describe to you the like of the mason-bricklayer. His kidneys are painful [his work pains him]. When he must be outside in the wind, he lays bricks without a loincloth. His belt is a cord for his back, a string for his buttocks. His strength has vanished through fatigue and stiffness, kneading all his excrement. He eats bread with his fingers, although he washes himself but once a day.

In contrast with the other wonders, there is a surfeit of information on some aspects of the pyramids—the literature, both by professionals and enthusiasts, is greater than that on all the other wonders combined.[23] Here, I will concentrate on the science of the pyramids, and their associated constructions, as well as their intended occupants.

The construction of commemorative tombs in Egypt started in about 3100 BCE with relatively modest buildings whose purpose was simply to protect the body. However, the burial of valuable objects with the body increased grave robbing, which in turn spurred the construction of ever larger and more complex structures. Bigger tombs could be filled with more grave goods, commonly exceeding existing resources, and therefore almost always necessitating the plunder of older tombs. This "tomb race" reached an apogee in about 2550 BCE when the pyramid complexes at Giza were built over a period of only sixty years. Subsequently, those in power seem to have realized that this strategy for the protection of the pharaoh's body was an expensive failure as the tombs were far too conspicuous. Subsequent tombs were smaller and less elaborate, and in 1525 BCE, after about 120 pyramids had been completed, a new approach was tried using unmarked underground tombs in the Valley of the Kings, near Thebes (modern Luxor). Ultimately, this was no more successful as almost all of those tombs were also robbed in antiquity.

The scale and number of the funerary monuments in Egypt have led many people to think that the ancient culture was only dedicated to death and the afterlife, but that is a biased view. The dead were commemorated on the rocky edges of the desert, where the land had no agricultural value and buildings were isolated from the destructive influence of the river. After construction of the tombs, the main interest in these areas of the population was probably as a source of stone and grave goods. In contrast, fields in the valley and delta hosted a dynamic society, where buildings were continually adapted and rebuilt to suit the needs of the people. This constant process of rejuvenation was partly forced by annual flooding as well as the natural meandering of the river across the valley and delta, which has effaced so much of the cultural landscape (Plate 4a).

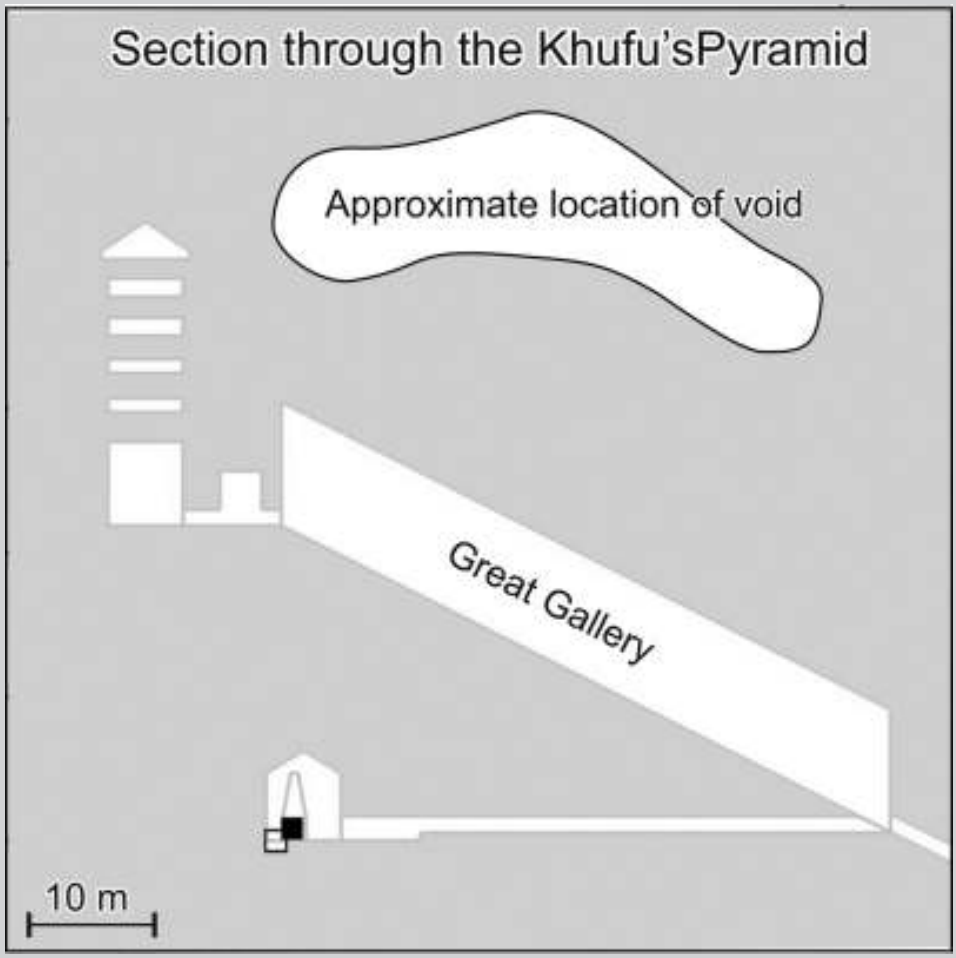
Construction of the first pyramid complex at Giza started in about 2552 BCE for the pharaoh Khufu. His name was associated with the earth god Khnum, who was in turn sometimes portrayed as an aspect of Ra, the sun god, but apart from that, we know very little about Khufu. The only image to survive is a disputed statuette 10 cm high.

The exterior form of his tomb was a four-sided pyramid closely aligned to the cardinal directions.[29] The base of each side was 230 metres long and the whole structure rose at an angle of 52° to an original height of 146 metres.[30] The exterior was faced with high-quality white Tura limestone blocks carefully smoothed and fitted together. The lower parts of the casing were inscribed with hieroglyph inscriptions and later with graffiti carved by visiting tourists or their guides.[2] This casing is largely missing and what we see now is the core of roughly shaped blocks of lower-quality limestone, somewhat spoiling the desired effect of the architects. The whole structure had a volume almost ten times larger than that of earlier monuments, 2.6 million cubic metres, making it the largest stone pyramid in the world.

The austere exterior of the structure belies a complex interior of three interconnected main chambers.[23] The largest and highest chamber was lined with huge granite blocks. The middle chamber, together with the galleries and tunnels, was mostly lined with high-quality limestone blocks, like that used for the casing on the outside of the pyramid. The lowest chamber was cut into the underlying bedrock but never finished. Recent geophysical research has revealed at least one formerly unknown chamber within the pyramid (see box 2-2: Hidden Chambers).[31]

The Great Pyramid was the outer defence for Khufu's body. The next layer of protection was a massive granite sarcophagus placed in the highest chamber during construction. Within this were placed inner coffins, probably of wood and gold, if we can go by those of later pharaohs. These were probably decorated with semi-precious stones like carnelian, lapis lazuli, and turquoise and objects made of a ceramic material now called Egyptian faience (see box 2-3: Gemstones and Imitations). Within all these protective layers lay the mummified body of the pharaoh.

Box 2-2 Hidden Chambers



Section through the Khufu Pyramid. Image by author after Morishima, K., et al., 2017, Discovery of a big void in Khufu's Pyramid by observation of cosmic-ray muons. *Nature* 552(7685): 386–390.

There have been many suggestions that the pyramids have hidden chambers but until recently it was not possible to investigate this non-destructively. This has changed with the introduction of a new method, muon tomography. A muon is a subatomic particle that resembles an electron but is heavier, which enables it to penetrate through hundreds of metres of rock. Muons are produced in the upper atmosphere by the impact of other subatomic particles from space and hence penetrate the pyramids from all directions. Large instruments placed around and inside the pyramid detect the number and direction of muons, which can be used to reconstruct a 3D image of the interior, like a medical X-ray scanner. The method cannot be used to find smaller voids but is good for larger structures. This work has revealed a chamber similar in size to the Great Gallery, but about 30 metres above it.[31] The next step will be to get a camera in, which will necessitate drilling a hole.

Box 2-3 Gemstones and Imitations

Many different types of semi-precious materials were buried with the pharaohs, but four stand out: the natural gemstones, carnelian; turquoise; lapis lazuli; and the artificial ceramic, "Egyptian" faience.

Carnelian, a reddish-brown natural gemstone similar to chalcedony and agate, is made up of crystals of silica (SiO_2) minerals that are so small that they cannot be seen under an optical microscope. It crystallizes out from watery solutions close to the surface and its red colour comes from iron minerals such as haematite (Fe_2O_3). This popular stone was commonly obtained from a locality now called Stela Ridge, near Aswan, but there may have been other source.[82]

The gemstone turquoise was first used in Egypt as long ago as 3000 BCE.[83] It was likely incorporated into many of the objects buried with the pharaohs at Giza and was used in items from the tomb of Tutankhamun, some 1,200 years later. Turquoise ($CuAl_6[PO_4]_4[OH]_8 \cdot 4H_2O$) forms when rainwater percolates through basalt lavas, oxidizing iron and copper sulphides to make an acidic copper solution, which then dissolves aluminium from feldspar and phosphorus from the mineral apatite. When this solution reaches the underlying rocks, the acid component is neutralized by calcite in the sandstone and the turquoise precipitates out in the form of nodules or veins in cracks. The most important mines were at Sarabit Al Khadim, in the western hills of the Sinai Peninsula, where turquoise was found close to the surface.

Lapis lazuli, another natural gemstone, was always an expensive material as there was only one source in antiquity, Sare Sang in the mountains of NE Afghanistan, where exploitation started in 7000 BCE and continues to this day.[84] The gemstone was formed by the chemical alteration of marble. Its distinctive component is the mineral lazurite ($[Na,Ca]_8[AlSiO_4]_6[S,SO_4,Cl]_{1-2}$), whose intense blue colour is due to the presence of sulphur ions in the structure. The use of lapis lazuli in Egypt and Assyria testifies to the existence of long-distance trade early in the history of humanity. The expense of true lapis lazuli led to the development of a substitute: deep blue artificial glass, as seen in the famous mask of Tutankhamun.[85]

Egyptian faience is a blue-green self-glazing ceramic that was used to make small objects in imitation of turquoise or lapis lazuli.[86] A paste of quartz sand, lime, copper-bearing materials, and natrun was shaped into the desired form. When it was fired, a copper-bearing silicate liquid formed and moved to the surface, where it crystallized as a blue glaze.[50] The quartz and copper may have been derived from a waste product, the powder made when hard stones were cut using copper tools and sand.

The pyramid was the largest part of a funerary complex that stretched eastwards to the Nile valley (Figure 2-2).[26–28] The pyramid itself was enclosed in a wall, broken on the eastern side by a mortuary temple. There were several large pits around the pyramid, two of which contained dismantled wooden boats that appeared to have been used briefly, perhaps for the funeral ceremonies. A roofed causeway led from the pyramid towards the valley temple and its harbour that was in turn linked to the Nile. All of these constructions were made of fine limestone and granite.

All of Khufu's mortuary complex has suffered over the years: the pyramid has lost all of its smooth outer casing, which was removed to build Cairo; little remains of the mortuary temple, except the basalt floor; most of the causeway has been destroyed, largely during the last 150 years; and as for the valley temple, only traces of its basalt pavement have been found, deep under the suburbs of Cairo.[23] Khufu must have had his palace near the pyramid complex and the scant vestiges of a large building to the south of the valley temple may be all that remains.[32] It would have been close to the Nile at that time.

Khufu was succeeded by his sons, first Djedefre, who ruled for ten to fourteen years and built a pyramid complex at Abu Rawash, 10 kilometres to the northeast of which little remains (Figure 2-8) and then Khafre, who ordered the construction of the other large pyramid on the Giza Plateau. Khafre's mortuary complex was started in about 2520 BCE, shortly after the Great Pyramid was finished. The pyramid

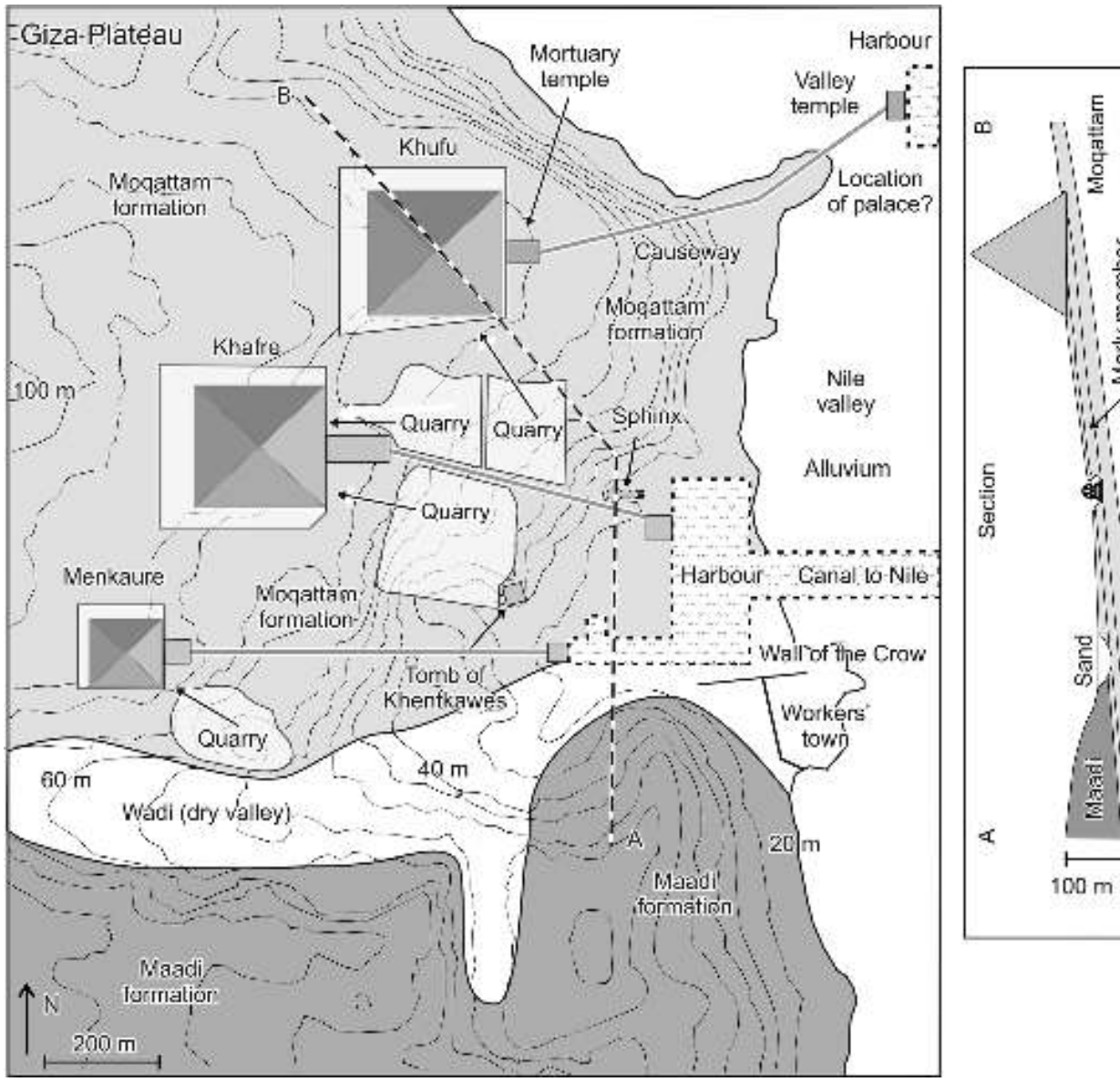


Figure 2-2: The bedrock on the main part of the Giza plateau is a relatively well-cemented limestone called the Moqattam formation. The rocks south of the wadi (normally dry valley) are younger and dominated by marly limestones of the Maadi formation. Map created by the author after Lehner, M. and Z.A. Hawass, 2017, Giza and the Pyramids. Thames & Hudson Ltd; Klemm, D.D.R.; Klemm, 2010, The stones of the pyramids: provenance of the building stones of the Old Kingdom pyramids of Egypt. De Gruyter: Berlin, Germany; New York; Raynaud, S., et al., 2010, "Geological and Topographical Study of the Original Hills at the Base of Fourth Dynasty Egyptian Monuments of the Memphite Plateau." *Bulletin de la Société Géologique de France* 181(3): 279–290.

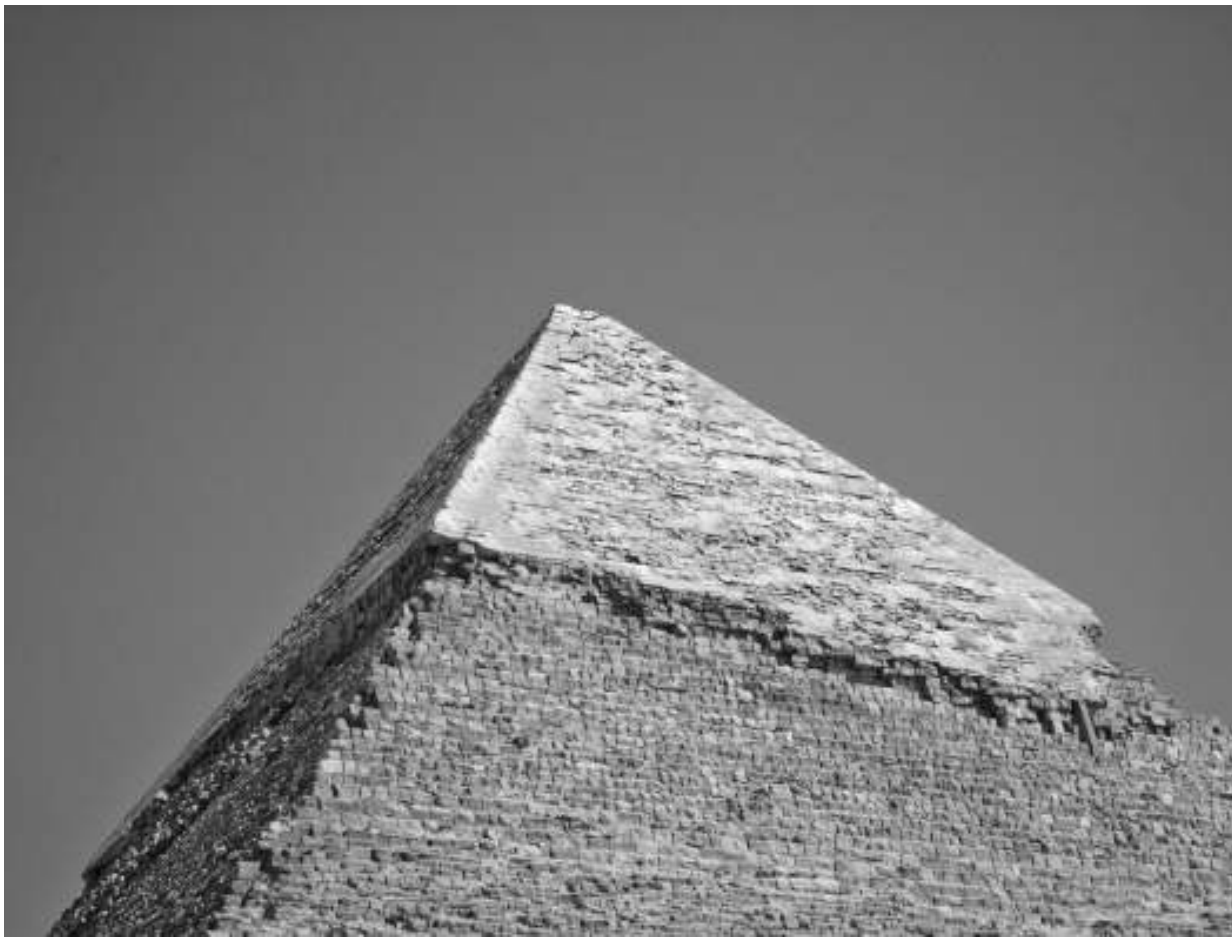


Figure 2-3: The only place where the outer casing of fine-grained Tura limestone is still intact is on the upper part of Khafre's Pyramid. Photo courtesy of the author.

itself is almost as large as Khufu's, with a similar shape and orientation. Most of his pyramid was also encased in fine Tura limestone blocks, which have survived only at the top (Figure 2-3). The bottom layers of the casing, made of granite, are mostly gone. The mortuary temple at its foot was larger than Khufu's but again has been largely destroyed. The walls were of limestone faced with granite, including some very large blocks weighing one hundred to four hundred tons each. The floor was of alabaster, a particularly soft rock made of gypsum. The bed of the causeway is largely intact, but its walls and roof have disappeared.

The valley temple of Khafre lies at the eastern end of the causeway (Figure 2-4). It is well preserved and has been described as "the most remarkable building in the Old Kingdom."[22] The outer walls were

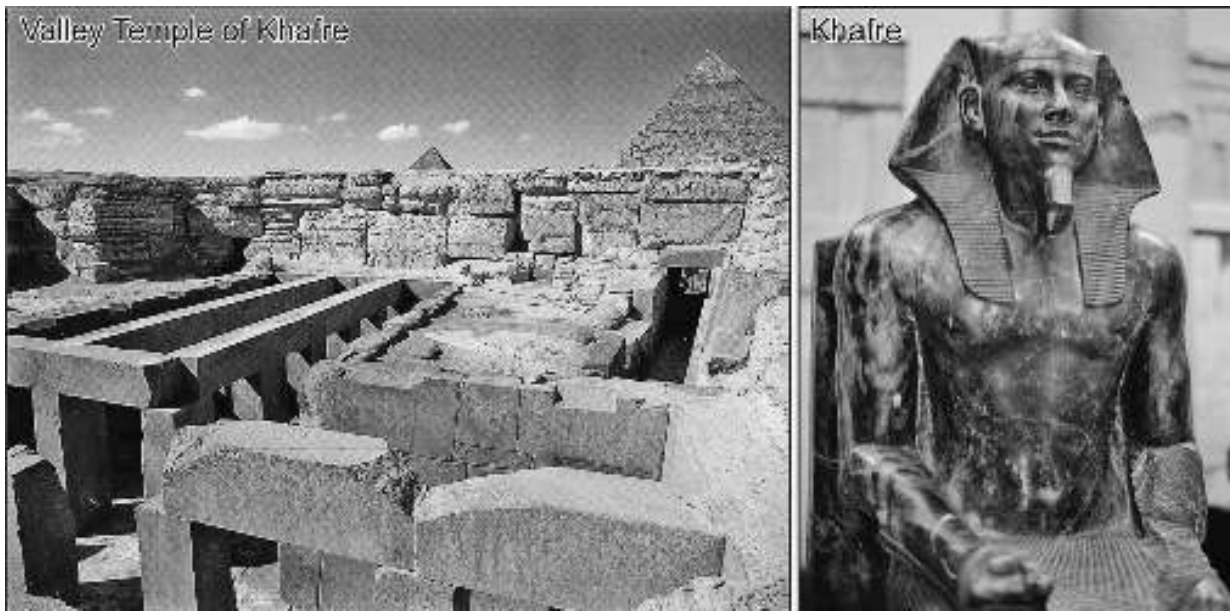


Figure 2-4: The interior of the Valley Temple of Khafre was made of huge blocks of Aswan granite and housed a life-sized statue of the pharaoh carved from gneiss. Photos Jon Bodsworth / Wikimedia Commons, Copyright free.

made of limestone, the interior was beautifully finished with granite walls, pillars, and lintels, and it was floored with basalt and alabaster. A fine statue of Khafre made of grey-green gneiss was found under the floor of the temple and must have originally been in a prominent place in the monument (Figure 2-4).

The third major pyramid at Giza was built by Menkaure, son of Khafre. It was started in about 2487 BCE, shortly after the completion of Khafre's Pyramid. The structure was similar to that of the large pyramids: a core of local limestone was largely faced with fine Tura limestone, except at the bottom 15 metres where beautifully trimmed granite blocks were used (Figure 2-5).

Excavators found a magnificent fully carved sarcophagus in the burial chamber.[33] It was described as made of basalt, but it is not possible to check because it was lost at sea in 1838 during transport to the British Museum. It is more likely that it was made of a dark granodiorite or even grey gneiss, both of which were available in large blocks. The sarcophagus was carefully drawn and its style suggests that it may not be the original one, but a replacement made in the 6th

Figure 2-5: The lower parts of the Pyramid of Menkaure were finished with granite blocks, which were smoothed where they faced the pyramid temple, now largely destroyed. Photo courtesy of the author.

century BCE. Nearby, there are three smaller, unfinished pyramids also with granite casings, one of which was probably for Menkaure's wife. The mortuary temple was made of limestone and partly faced with granite. The base of the limestone causeway still exists, as does the unfinished valley temple.

The wonders of Giza are completed by the Great Sphinx, a huge mass of rock carved into the form of a head, now missing the nose and beard, on the body of a lion, the whole facing a sizeable temple (Figure 2-6). Although it is generally thought that the Sphinx was carved on the orders of Khafre as part of his pyramid complex, it may even predate the pyramids at Giza. It was carved from a low hill that may have resembled a lion facing east, towards the rising sun.[34] Khufu

Figure 2-6: The Great Sphinx was cut from a natural outcrop and has been repaired many times over the ages. The head is well preserved as the limestone at this level is relatively pure and well cemented. In contrast, the body has weathered extensively as it was cut from a layer of soft, marly limestone and has also suffered from the destructive effects of rising groundwater. Photo courtesy of the author.

may have chosen to construct his pyramid on the Giza Plateau precisely because there was already a cult established there.[23]

Why Pyramids?

For about 1,500 years, most Egyptian royal funerary complexes were dominated by four-sided pyramids, but what was the inspiration for this simple geometric form? Some people propose that the shape was a development of early step pyramids, but that idea just puts off the explanation to an earlier period.

Figure 2-7: The shape of hills in the Egyptian desert may have inspired the geometrical form of the pyramids. Photo courtesy of the author.

One possibility is that the shape was linked to the creation myth of the ancient Egyptian religion, in which a mound arose from the primordial waters and caught the first rays of the sun.[23] This mound was symbolized by the sacred Benben stone (possibly "the radiant one") at Heliopolis, which has not survived, and in turn by the "benbenet," which was the uppermost stone of the pyramids. This connection to the creation myth was renewed each day when the rising sun illuminated the top of the pyramid.

Now a four-sided pyramid does not resemble a mound of sand, which would tend to be conical, so what is the origin of the shape? The orientation of the four sides corresponds to the cardinal directions, manifesting the association of the pharaoh with the sun. The inclination of the sides could have originally reflected the angle of repose of wet sand or the slopes of hills seen in this barren rocky landscape (Figure 2-7). In practice, the pyramid sides were steeper, which had the advantage that sand did not accumulate on the sides of the structure. The actual angle of the sides was not standardized and tended to become steeper with time, perhaps reflecting a better understanding of the engineering and technological challenges.

There is an enormous amount of literature on the mathematical and historical significance of the pyramids' dimensions but critical analysis suggests that the shape was chosen somewhat arbitrarily and determined by two parameters: the length of the base in royal cubits (~53 centimetres) and the angle in *seked* units. The latter is the offset in palms for a rise of one royal cubit of 7 palms.[35,36] For example, a seked of 7 would be equivalent to an angle of 45 degrees—7 palms upwards and 7 palms sideways. Another critical factor was that the pyramid had to be completed before or shortly after the pharaoh died, because without the installation of the topmost stone the pyramid could not function as a spiritual stair to help the deceased to ascend to the sky.

Construction of the Pyramid Complexes

All the pyramid complexes were constructed on the edge of the Western Desert, just beside the Nile valley (Figure 2-8). This is usually explained on a religious basis, as the "Land of the Dead" lay to the west, but this seems to me to be a weak argument, especially as the later burials in the "Valley of the Kings" were east of the Nile. A more valid reason may be that the first illumination of the top of the pyramid at dawn was most easily seen by people in the Nile valley if the structures were to the west. However, it may be that the pyramids were sited on the west side of the Nile for practical reasons.

The bluffs to the west of the Nile are generally much lower and less steep than those to the east (Figure 2-8), making access easier for the transport of materials and people during construction and subsequent religious ceremonies. This difference in relief may be related to the geologically recent opening of the Red Sea Rift and the uplift of its margins, which also produced the Red Sea mountains to the south (Figure 2-16).

The western bluffs had another more important advantage:[28,37] at that time the Nile or a major branch of it, flowed along the western part of the valley.[38] It seems likely that wealth, as in most civilizations,

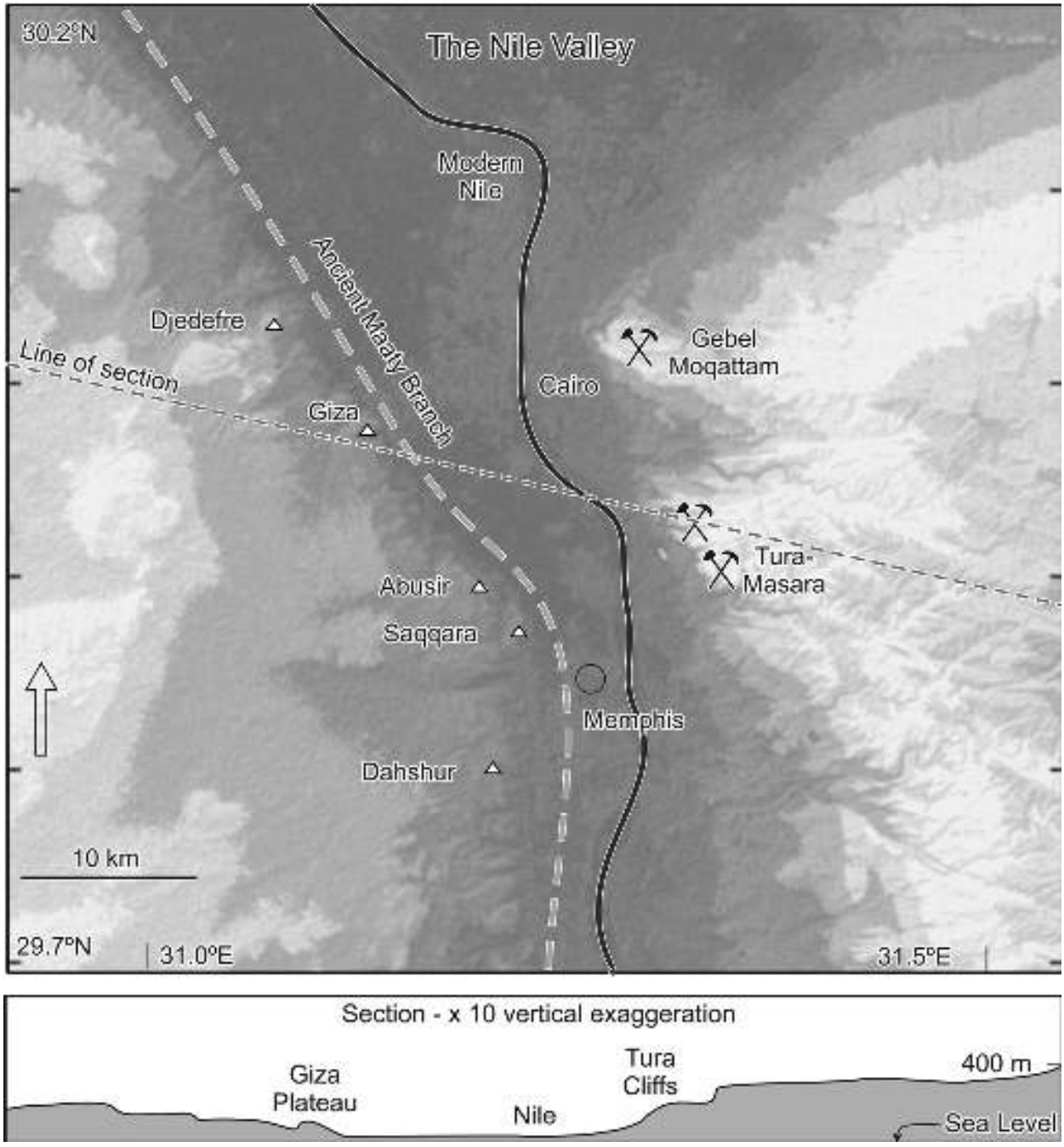


Figure 2-8: The main branch of the Nile has meandered across much of the valley and was at its westernmost position when the Pyramids were constructed at Giza. Image by the author.

was concentrated near the most navigable part of the river; hence it is likely that the Royal Palaces were nearby. The presence of the waterway made transportation of stone from quarries on the eastern bluffs of the valley, and granite from Aswan far to the south, much

easier although movements of the heaviest watercraft were probably restricted to the flood season when the Nile rose by as much as 7 metres (Figure 2-16, Figure 8-10).

This waterway may have been a significant part of the landscape of central Egypt: it probably divided from the principal channel of the Nile some 220 kilometres to the south and flowed northwards to deliver water to the Fayum depression, then on to Giza and the delta.[39] It was relatively shallow, as it was constantly filled by sand blown in from the desert to the west. Such sluggish streams cannot erode their banks and hence tend to stay in the same place, which may have led to its name, *Maaty*, from the word *Maa*, one meaning of which is stability.[7] Since the time of the Giza Pyramids, flow in the Maaty decreased as drier climates increased the amount of sand blown into the valley and tectonic forces tilted the delta and valley to the east: now all that is left is a small drainage ditch.[13] The loss of this important waterway may have contributed to the decline and eventual abandonment of Giza, Saqqara, and the other mortuary sites on the west bank.

Another factor in the choice of the Giza Plateau may have been the presence of a marginal lake or marsh impounded between the wadi mouth and the levee (raised bank) of the Nile, similar to that proposed for the pyramid fields of Saqqara and Abusir.[40] Such a lake would have been filled by winter flash floods, as well as the summer inundation by the Nile, and would, no doubt, have made transportation of people and construction materials from the Nile to the site far easier, especially if it was deepened in places to make canals.

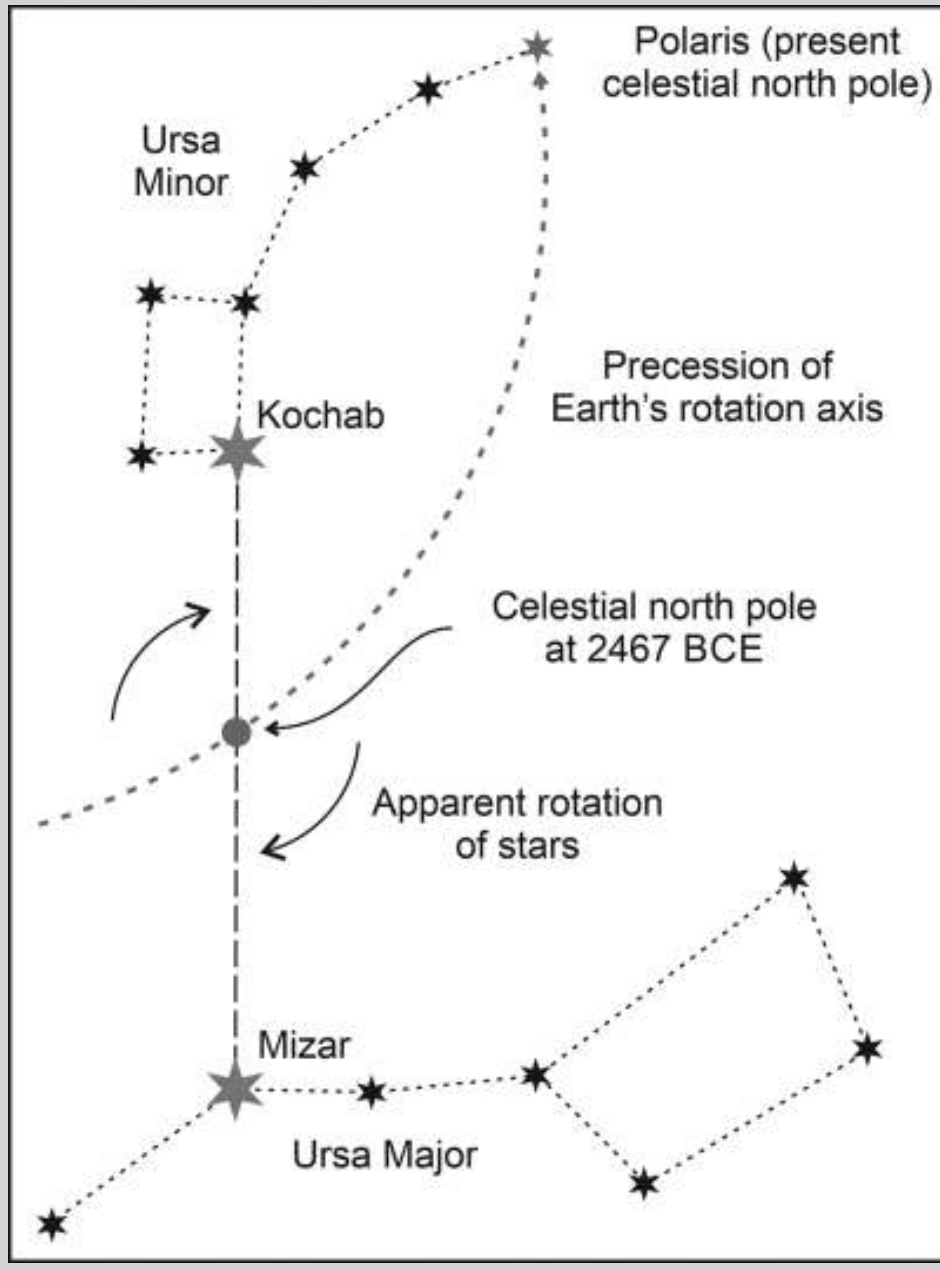
The low bluffs, the proximity of the Nile, and presence of marginal lakes may have been points in favour of the western side of the valley, but the final choice of the site was probably determined by the nature of the local stone. Khufu's predecessors had built their burial monuments at Dahshur, 25 kilometres south of modern Cairo, but it was not a good site for his new project: the bedrock was so rich in clay that it could not bear the weight of the proposed pyramid, and there was no longer enough limestone nearby that was strong enough for construction.[26] The site near Giza was much more suitable. There was

plenty of space on this low plateau beside the Nile where the bedrock was a strong well-cemented limestone that made a good foundation, and which could also be cut into blocks to make the pyramid and other parts of the mortuary complex. In addition, there was a low hill that could be incorporated into the pyramid to reduce the amount of stone.[27]

There was an elaborate system of canals and harbours in the valley, but it is now covered by the urban sprawl of Cairo. Traces of the ancient geography has been revealed during exploratory drilling and archaeological excavations, mostly associated with major engineering projects such as sewer construction. Despite these advances, we don't really know how canals and harbours were built and maintained. It was easy to dig down to the water table, which was at its deepest just before the annual inundation, but to go further it would have been necessary to dredge, as there were no pumps or other water-lifting devices powerful enough to dewater the excavation. Dredging seems to have been such an unpleasant task that it was probably consigned to slaves and hence never recorded. They may have used specialized boats or barges similar to those used by later civilizations (see box 6-7: Dredging Techniques).

Once the site for the pyramid had been selected, the base for it had to be laid out accurately.[23] Although we do not know exactly how this was done, one possibility is that workers cut a trench around the future base and filled it with water to establish a horizontal surface. The sides of the pyramids were closely aligned to the cardinal directions, north-south-east-west, presumably because the pharaohs were associated with the sun god Ra. It is relatively simple to find the approximate direction of north from solar observations, for example, by noting the position of shadows cast by a vertical stick or the orientations of sunrise and sunset.[29,41] However, there are minor errors in the orientation of the pyramids that appear to vary systematically with time, which has suggested to some people that the positions of certain stars may have been used instead (see box 2-4: Alignment Using the Stars).

Box 2-4 Alignment Using the Stars



View north from Giza on 23 August 2467 BCE. Image by author after Spence, K., 2000, Ancient Egyptian chronology and the astronomical orientation of pyramids. *Nature* 408(6810): 320–324.

On a clear night, it is easy for us to find true north as the star Polaris is close to the celestial North Pole, the point about which the sky appears to revolve. However, this was not true 4,500 years ago, because the celestial pole traces out a huge circle in the sky with a revolution every 26,000 years, called the precession of the

axis. When the pyramids were constructed, there was no star at the celestial North Pole, but there were two bright stars about 10 degrees on either side of the pole:[87] Mizar, which lies in the constellation Ursa Major (= *Great Bear*, *Plough*, *Big Dipper*), one of the most easily recognized constellations, and Kochab in the constellation Ursa Minor (= *Little Bear*, *Little Dipper*). Once each night the two stars were directly above each other and this direction was close to true north. The north direction could thus have been determined by lining up the stars using a plumb line or a vertical surface. This procedure was precise only in 2467 BCE and there were errors of about half a degree per hundred years before or after. Minor misalignments of the pyramids that appear to vary with time suggest that this method was used by the ancient Egyptians. Today, we can use the misalignments to date the start of construction within five years: The Pyramid of Khufu has been dated at 2552 BCE, Khafre at 2520, and Menkaure at 2487. Although these dates are about forty to fifty years older than a recent compilation, they are within the range of other studies.[23,88]

Quarries on the Giza Plateau supplied blocks for the cores of the pyramids (Figure 2-2).[26] A large quarry lying to the south of the Khufu pyramid was excavated to a depth of over 30 metres but is now partly filled in with rocky debris—it alone supplied all of the limestone for the construction of the Great Pyramid, some 2.6 million cubic metres! The fact that the tombs of Khufu's children were dug into the west wall of the quarry suggests that it was not viewed as an industrial site, but more as a new landscape (Figure 2-9). The builders of Khafre's Pyramid used several different quarries and left a ridge for the causeway linking the pyramid and nearby valley temple. Menkaure's Pyramid was mostly built from stone quarried at a single site to the southeast.

An ancient quarry beside the Pyramid of Khafre may give us clues to how blocks of stone were extracted (Figure 2-10).[42] Trenches were cut 1 to 2 metres apart down and up to 1 metre deep to a weaker layer of rock and then the blocks were prised out with levers.[43] Workers

Figure 2-9: The western wall of the biggest limestone quarry on the Giza Plateau houses the tombs of Khufu's children. The Pyramid of Khafre is in the background. Photo © Per Storemyr.

excavated the trenches mostly using blades and axes made of flint (= chert), a rock that forms rounded masses in some limestones by the recrystallization of silica from the skeletons of sponges. It is mostly composed of fine-grained interlocking quartz crystals that are much harder than calcite, the dominant mineral in limestone. The main source of high-quality flint was 200 kilometres to the south, at Wadi el-Sheikh.[44] Copper tools may also have been used to extract and shape the blocks (see box 2-5: Copper Stone-Working Tools).

The size, quality, and shape of the blocks that made up the core of the pyramid varied immensely. Some of those that we see today at the base pyramid were carefully trimmed and probably backed the fine limestone casing that has now been removed (Figure 2-11). However, further up, and in the interior, blocks did not have a standard size and were piled up with little effort to fit against their neighbours—gaps were filled with smaller blocks and rubble, cemented with gypsum

Figure 2-10: The trenches used to extract stone blocks are still visible in a quarry beside the Pyramid of Khafre. Weaker layers in the limestone can be seen in the walls of the quarry—these were used to shear off the base of the blocks. Some people have interpreted this site differently: that it was used to quarry blocks for repair, or that the channels were simply a way of flattening the surface that was never completed. Photo © Per Storemyr.

mortar. Blocks in the lower layers averaged 1 × 2.5 × 1–1.5 m and weighed 6 to10 tons, but those used higher up were smaller, typically 1 × 1 × 0.5 m, with an average weight of 1.3 tons.[45]

Gypsum mortar was first used in Egypt in the 4th millennium BCE. It was made by heating rocks rich in gypsum ($CaSO_4 \cdot 2H_2O$) to 100–170°C to remove the water in the mineral. The resulting powder ($CaSO_4$; "Plaster of Paris") was mixed with water to make a slurry that acted both as a lubricant for sliding blocks and filling gaps. In a short time, the powder recombined with water to form interlocking crystals of gypsum. The raw material of the mortar was probably gypsite, a kind of soil that develops in arid regions over rocks rich in gypsum: groundwater dissolves gypsum from the rock and evaporation draws the water towards the surface where it crystallizes. Large deposits of

Box 2-5 Copper Stone-Working Tools

Stonecutter with chisel and mallet from Deir el-Medina.
Image © Fitzwilliam Museum, Cambridge.

Nowadays, we shape stone with metal tools tipped with hard materials such as silicon carbide, diamond, and corundum (emery), but these were not available in ancient Egypt, though the latter was used in ancient Greece (see Chapter 5). At the time of the Giza Pyramids, most tools were made of copper, which is, unfortunately, softer than granite, but some may have been alloyed with arsenic, either on purpose or accidentally by smelting arsenic-rich ore, making a slightly harder metal.[89] Bronze, an alloy of copper and tin, was only used extensively much later (see Chapter 7). Limestone was carved with sharp copper chisels hit with a wooden mallet but harder materials required a different technique: stone was abraded using a slurry of quartz sand and blunt saws, bead drills,

and tube drills. Such tools wore out fast but the copper metal could be recycled from the waste or used to make faience (see box 2-3: Gemstones and Imitations).

While copper was necessary for the construction of the pyramids, it was not abundant in ancient Egypt. The huge deposits on Cyprus were not known at that time, so special expeditions were organized from the Red Sea port at Wadi el-Jarf to extract copper from the western Sinai Peninsula, where many small metal deposits occurred, mostly as layers in sandstone (Figure 2-16).[51,90] Although there was a wide variety of different copper minerals in those sedimentary rocks, the most important was probably malachite, whose bright green colour makes it easy to recognize in the field and to separate from the waste minerals. Piles of waste ("slag") show that some ore may have been refined near the mines, suggesting that some fuel (wood) was available nearby—reduction of copper ore to metal needs charcoal and temperatures over 1000°C. Although there is little vegetation in the region now, the ancient climate may have been wetter with trees growing in more sheltered places. There were also deposits of turquoise that may have been exploited by the same expeditions. The region is now known as a source of manganese, a metal not used in antiquity.

gypsite occur just southeast of Cairo at Helvan and ancient quarries have been found near Amarna 200 kilometres to the south.[46] The presence of gypsum mortar may have inspired some people to suggest that the pyramids were made of poured concrete, but there is no evidence for this (see box 2-6: Were the Pyramids Made of Concrete?).

The exterior casing of the pyramids, and the linings of the galleries and chambers, were mostly made of fine-grained limestone from underground quarries at Tura-Masara and possibly Gebel Moqattam, both on the east side of the Nile valley (Figure 2-8).[47,48] The earliest quarries were large, rather irregular openings in the cliffs, up to 10 m high, but later excavations were more uniform, typically tunnels up to 20 metres wide and 450 metres, deep (Figure 2-12).

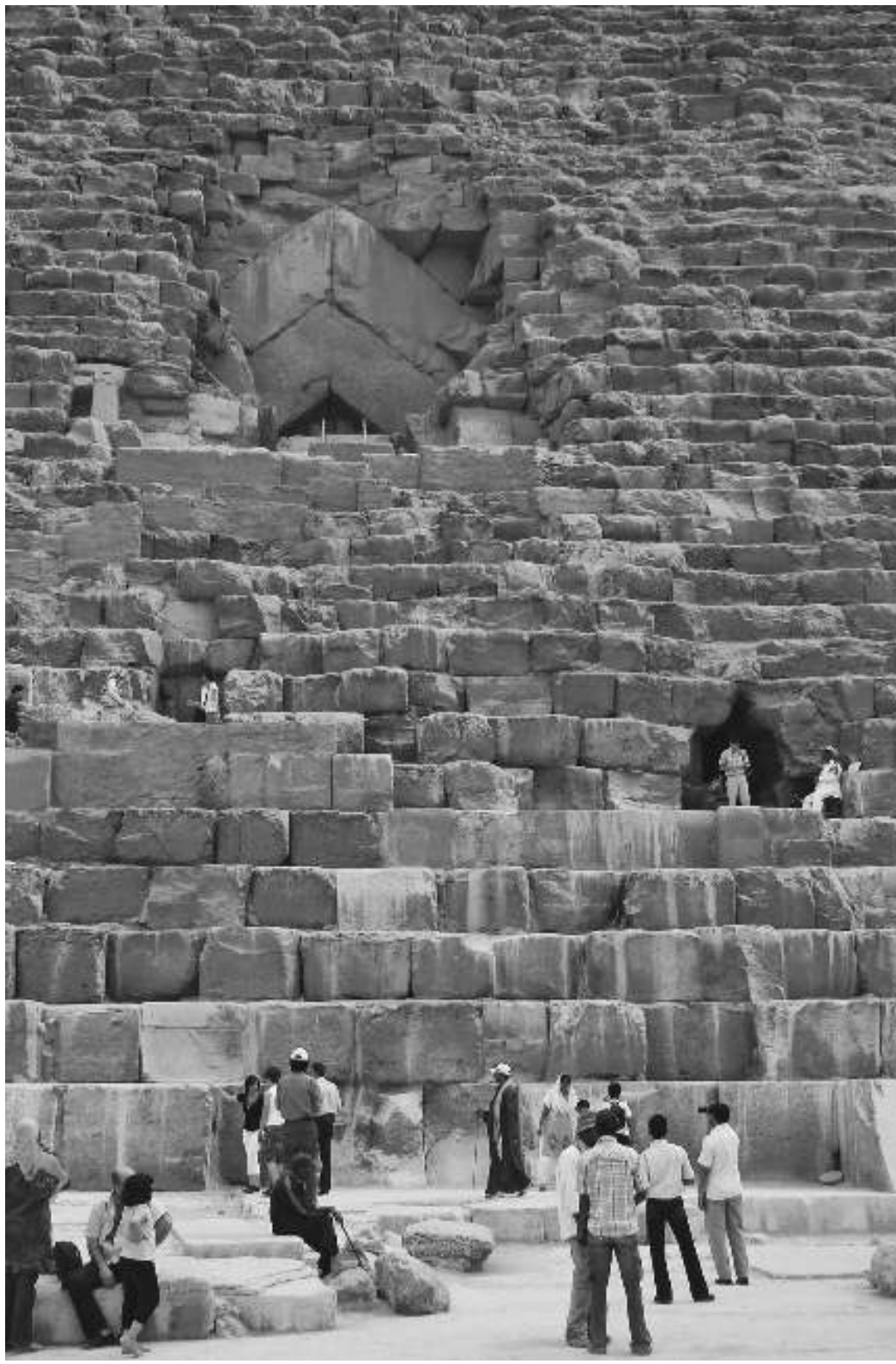


Figure 2-11: Blocks at the base of Khufu pyramid were precisely shaped but those higher up are much more irregular, with gaps filled with gypsum mortar. The original entrance to the tomb chambers is seen in the centre and that cut by tomb robbers is to the right. Photo © Hajotthu / Wikimedia commons, CC BY 3.0.

Box 2-6 Were the Pyramids Made of Concrete?

About thirty-five years ago, specialists in concrete chemistry proposed that the pyramids were made of concrete, prepared mostly from local materials and cast in place on the structure.[91] They proposed this idea as a simpler method of construction than cutting blocks and raising them into place. Their idea has been publicized in books and on TV but has no support from archaeologists and geologists familiar with the pyramids.[92,93] One problem with the theory is that the studies have mostly been in the laboratory and few samples from the pyramids have been analysed to see if they are actually concrete. Even then, it is not clear that the samples that were analysed were actually from the pyramids and the authorities have not permitted any further sampling. The idea of synthetic rock has been taken up by some physicists and chemists, who have applied exotic analytical techniques, but not the usual methods used by geologists such as a microscopic examination of thin rock slices. Analyses by geologists have not found any evidence for use of concrete, although it is well known that the space between some core blocks was filled with gypsum mortar.

A philosophical principle called "Occam's Razor" guides many branches of science: it says that among competing hypotheses, we should choose the one that makes the fewest assumptions. The "razor" cuts away extraneous arguments. In this case, the blocks of material used to construct the pyramids resemble the limestone of the region; the pyramids are surrounded by quarries large enough to have supplied all the rock needed to build the pyramids; and the ancient Egyptians were skilled enough to have cut, hauled, and placed the rock. Therefore, the most likely explanation is that the ancient Egyptians built the pyramids using locally sourced limestone.

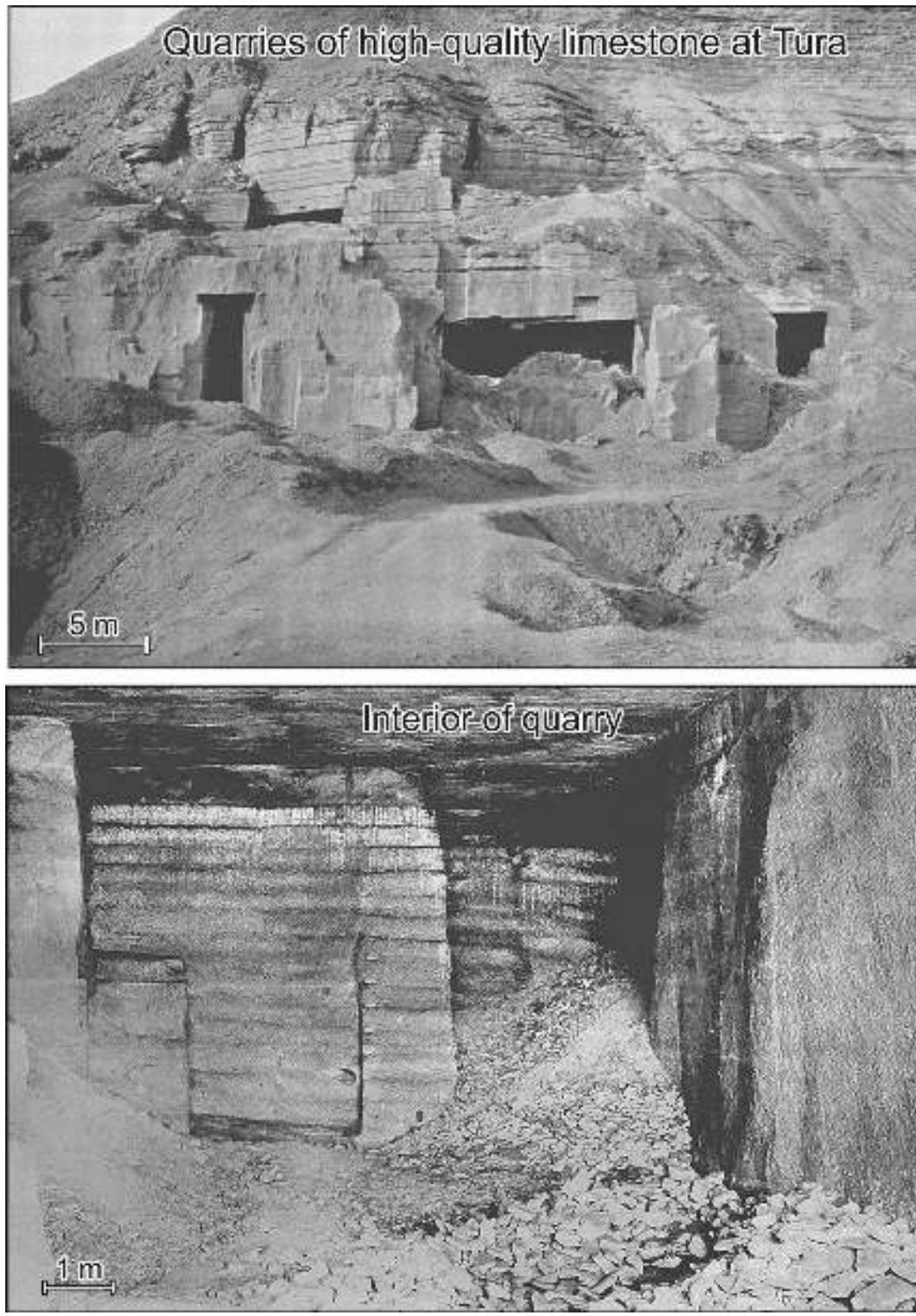


Figure 2-12: Quarries for high-quality finishing limestone were tunnelled into the cliffs on the east side of the Nile valley near Tura and some were later reused as dwellings. Excavation started at the top with a horizontal slot deep enough for the worker to climb in and chisel a vertical trench at the back. The blocks were then separated from the front and broken out along weak shale layers. Photos from Clarke, S. and R. Engelbach, 1930, *Ancient Egyptian Masonry: The Building Craft*. Oxford University Press, H. Milford: London.

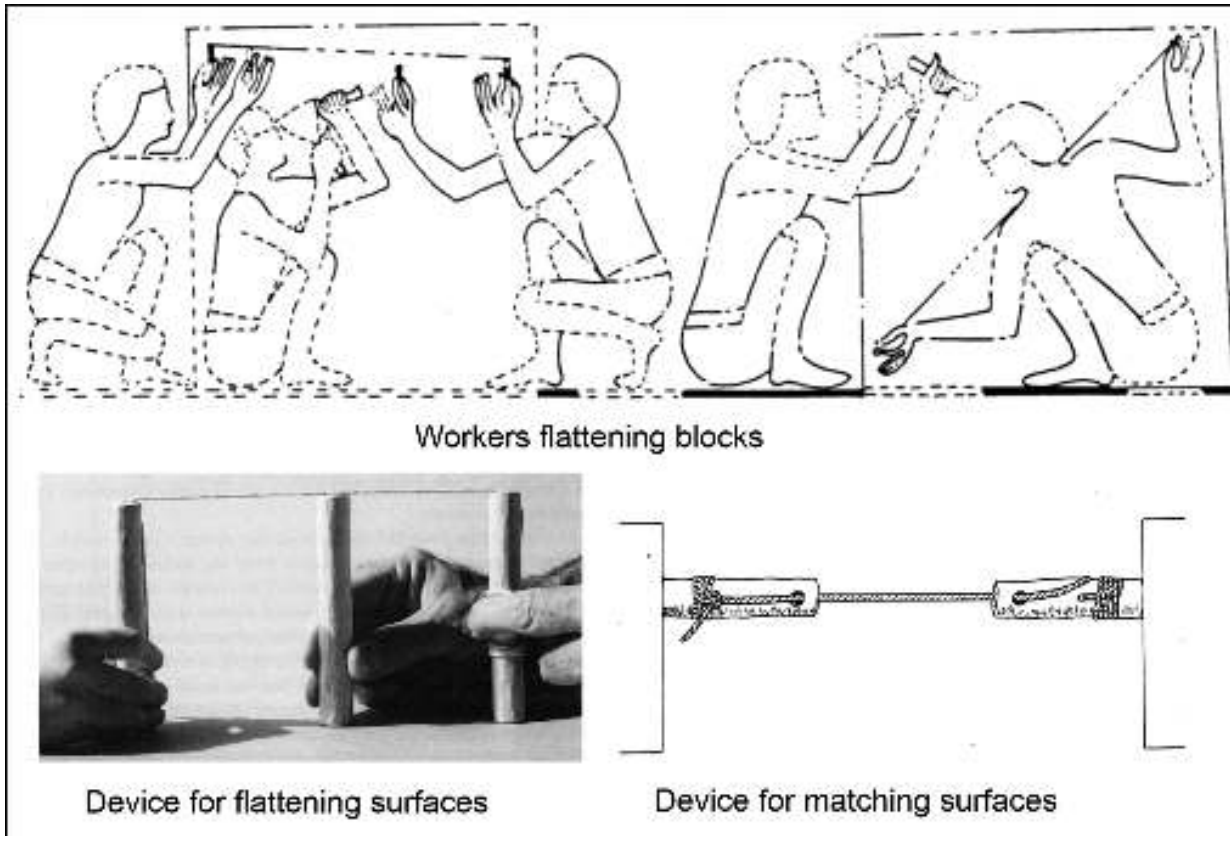


Figure 2-13: Two workers hold short rods with a tensioned cord. The flatness is checked with the third rod and adjusted with a copper chisel and mallet. The match between the surfaces of adjoining blocks could be verified using two rods attached with a cord before they were put together. Image by author after Stocks, D.A., 2003, "Immutable Laws of Friction: Preparing and Fitting Stone Blocks into the Great Pyramid of Giza." *Antiquity* 77(297): 572–578; Stocks, D.A., 2003, *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*. Routledge: London; New York.

The quarried blocks were roughly trimmed and loaded onto boats for transport to the construction site. Once the blocks arrived, the base and one side were smoothed and the block inverted before being placed on existing blocks (Figure 2-13).[49,50] The top and remaining sides were then flattened to accept further blocks.

Remarkably, we know quite a lot about quarrying and transport of the casing blocks from the "diary" of an official called Merer that was found in the remains of a port on the Red Sea.[51] For a period of several months, he describes what his team of two hundred men did each day at the quarries and on the boats: evidently, transport of the blocks from the quarries at Tura to the construction site took four

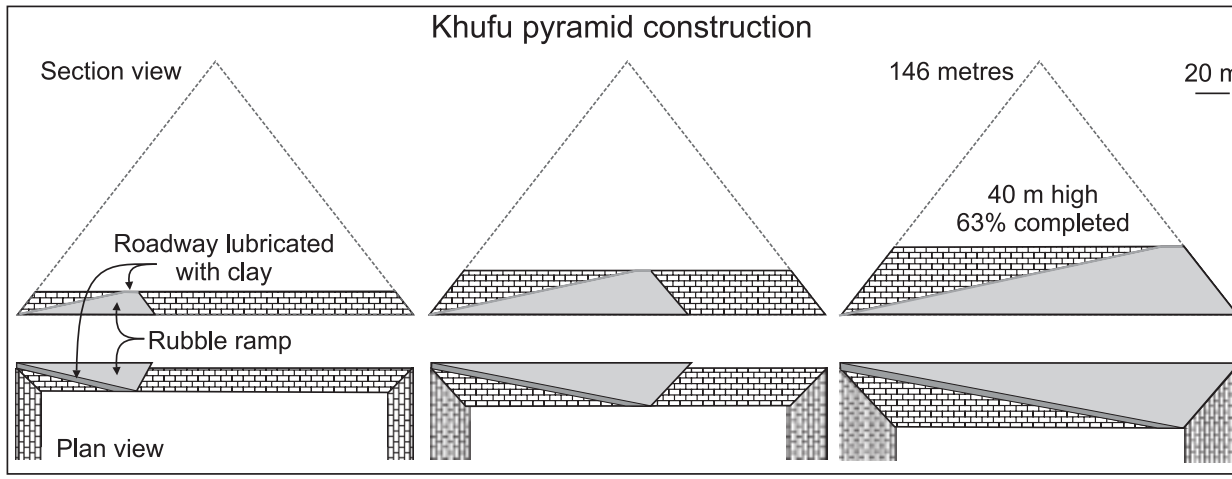


Figure 2-14: Raising blocks using a clay-lubricated ramp attached to one side of the pyramid. Image by the author.

days. Other details confirm that the vizier in charge of construction was Ankh-haf, the half-brother of Khufu, and that the pyramid was almost finished towards the end of Khufu's reign.

Immense numbers of large blocks had to be excavated, lifted, and put into place—Khufu's pyramid alone needed about two million of them. The process was rendered more complex as the blocks of granite and fine-grained limestone used for the galleries and chambers, as well as the huge sarcophagus of the pharaoh, must have been carefully installed at the same time as the coarse masonry of the core blocks. It seems logical that the outer casing blocks and their backing blocks were also installed at that time, although the outer faces may have been refinished later.

We do not know how the pyramids were constructed but it is clear that the ancient Egyptians had a lot of experience with such large projects and would have chosen the most efficient methods. There is no shortage of modern explanations and most involve either ramps or levers.[23]

It is commonly proposed that ramps were constructed around the pyramids and the limestone blocks were dragged up into position using rollers.[23] However, ramps are not mentioned by any of the ancient writers and there are no piles of broken rock that are sufficiently

large to be the remains of a ramp that went up to the top of the pyramid. However, remains of smaller ramps have been found next to some of the tombs around the pyramids, and the vast amount of debris in the former quarries could have been deposited there after a smaller pyramid ramp was dismantled.[23] An ingenious idea for "internal" ramps cut into the sides of the pyramid during construction would probably have left traces in the placement of the core blocks, which has not been observed.[26]

Although ramps projecting out from the pyramid are generally shown in illustrations of this method, it would have been easier to use ramps parallel to the edges, as one side would have been supported by the pyramid and the ramp could have been easily extended upwards from its upper end without resurfacing the entire ramp (Figure 2-14). It would have much easier to move the blocks if a lubricant was used, perhaps removing the need for rollers.[49] Clay is abundant in the desert and once wetted would have been suitable for the ramp, which had to be limited to a slope to 8°, otherwise the blocks would have slid back down. Once the blocks were on the pyramid construction platform, then gypsum mortar would have been the lubricant of choice as the excess would have cemented the underlying blocks. An 8° ramp could go up one corner to a height of 40 metres by which time almost two-thirds of the stone would have been in place (Figure 2-14). If the ramp was to continue higher, then it would have had to have been doubled in width so that it could swing back across the face of the pyramid, or continue around onto another face, and in either case, the volume of the ramp would have been increased enormously. This suggests that another approach was used to finish the pyramids.

The use of levers is suggested by Herodotus although we should recall that he was writing in the 5th century BCE, two thousand years after the construction of the pyramids:[53] "This pyramid was made after the manner of steps which some called rows and others bases: and when they had first made it thus, they raised the remaining stones with machines made of short pieces of timber, raising them first from

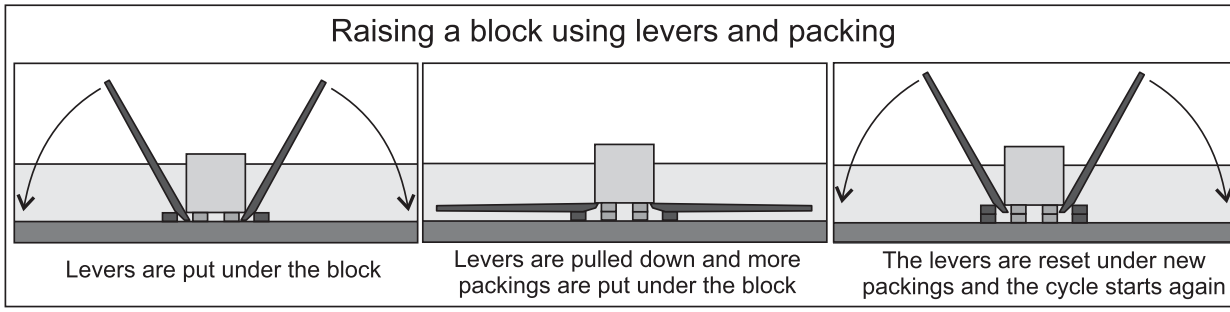

Raising a block using levers and packing
Levers are put under the block
Levers are pulled down and more packings are put under the block
The levers are reset under new packings and the cycle starts again

Figure 2-15: Raising stone blocks using levers and packings. Image by author after Hodges, P. and J. Keable, 1989, *How the Pyramids Were Built*. Element Books Ltd.: Longmead, UK.

the ground to the first stage of the steps, and when the stone got up to this it was placed upon another machine standing on the first stage, and so from this it was drawn to the second upon another machine; for as many as were the courses of the steps, so many machines there were also, or perhaps they transferred one and the same machine, made so as easily to be carried, to each stage successively, so that they might take up the stones; for let it be told in both ways, as it is reported." This explanation is not always easy to follow but could be interpreted in this way: large stone blocks were lifted a few centimetres using levers and then small packing blocks or pieces of wood were inserted underneath (Figure 2-15).[52] This cycle would have been repeated until the block was level with the next step when it would have been slid over onto it.

The most efficient approach would have been to use both edge ramps and levers. At the start of the project, ramps did not have to be very long and a huge number of blocks could have been moved rapidly into place. Later on, blocks would have still been dragged up to the top of the ramps and then raised up the side of the growing pyramid using levers.

Whatever construction method used, a large labour force had to be assembled, fed, and managed. Herodotus was told that one hundred thousand slaves worked for three months each year for twenty years. Recently, the project has been considered from several directions, such as modern dam construction using manual labour or total

energy requirements, and the consensus is that only ten thousand people would have been needed if they worked all year round.[54,55] These would have included stoneworkers, as well as cooks, bakers, butchers, and other camp hangers-on. We do not know where the builders for the first two pyramids were accommodated but Menkaure's "workers town" has been found in the Nile valley south of the wadi exit[23] (Figure 2-2). Excavations here suggest that most of the men were free rather than enslaved.[23] The location of the settlement was less than ideal as it was damaged by water from winter storms coming down the wadi every few years and a massive structure called the "Wall of the Crow" may have been built for protection. However, it is unclear why Menkaure would have put his workers here at all: perhaps the storms were such a new phenomenon that he felt that they would go away if ignored, a political view of ecological problems that continues to the present day.[39]

Unlike the pyramids, the Great Sphinx was carved in place, meaning that the builders could not choose the best stone for the project. The head was cut from a layer of harder and better-cemented limestone, the same as that quarried for the cores of the pyramids. However, the body was sculpted from a layer of poorly cemented marly limestone that has not survived as well—this rock is easily eroded and this is why the body has had to be repaired and refaced many times during the last four thousand years.

Shortly after the last pyramid at Giza was constructed, the whole site was abandoned and the more accessible parts were robbed for stone. Interest returned at the start of the New Kingdom period (16th to 13th centuries BCE) when many of the monuments on the Giza Plateau were rejuvenated, including the Sphinx. A beard was added to its face, and the whole painted in red, blue, and yellow.[23]

The construction of the pyramid complexes needed stone and other materials not only from local sources but also from distant regions. This brings us to look at the geology of Egypt, which differs so much from that of the Aegean and Mesopotamia, where the other Wonders were constructed.

The Geology of Egypt

To those accustomed to the mountainous landscapes of Greece and Turkey, Egypt comes as a shock: most of the country is quite flat, except for the hills that hug the west side of the Red Sea. This is not just something recent but reflects a geological history that has been long dominated by minor vertical movements of the crust, and not the horizontal continental collisions that made the mountains of the Mediterranean region. However, this does not mean that nothing interesting has happened here, just that we must search for it in landscapes that may appear at first glance to be somewhat monotonous.[56,57]

The geology of Egypt is dominated by three important layers of rock (Figure 2-16). The lowest and oldest unit (900 to 700 million years old) is mostly exposed east of the Nile, where the land has been uplifted along the flanks of the Red Sea rift and has been stripped of its younger sedimentary cover by erosion.[58,59] It is made of igneous and metamorphic rocks that have a complex history: it started with the formation of small ocean basins, which were then closed by tectonic forces that thrust the ocean floor up onto the land. Later, deeper parts of the crust were heated and deformed making a range of metamorphic rocks, including a grey gneiss that was quarried for statues and bowls (Figure 2-4). Parts of the crust melted and the resulting granitic liquids (magma) rose in the crust and eventually crystallized. Before they were completely cool, these hot rocks created huge convective movements of water that dissolved gold, copper, and other metals from the rocks. When these liquids cooled, they precipitated ore minerals creating the rich mineral deposits found in the Eastern Desert that have been exploited since antiquity (Figure 2-16, Plate 3b).

Granite and metamorphic rocks resist erosion better than sedimentary rocks so will tend to stand up as ridges—that at Aswan produced a step in the riverbed, creating the rapids at the First Cataract. This feature limited the movements of boats along the river, and thus often defined the territorial limit of ancient Egypt. In modern times,

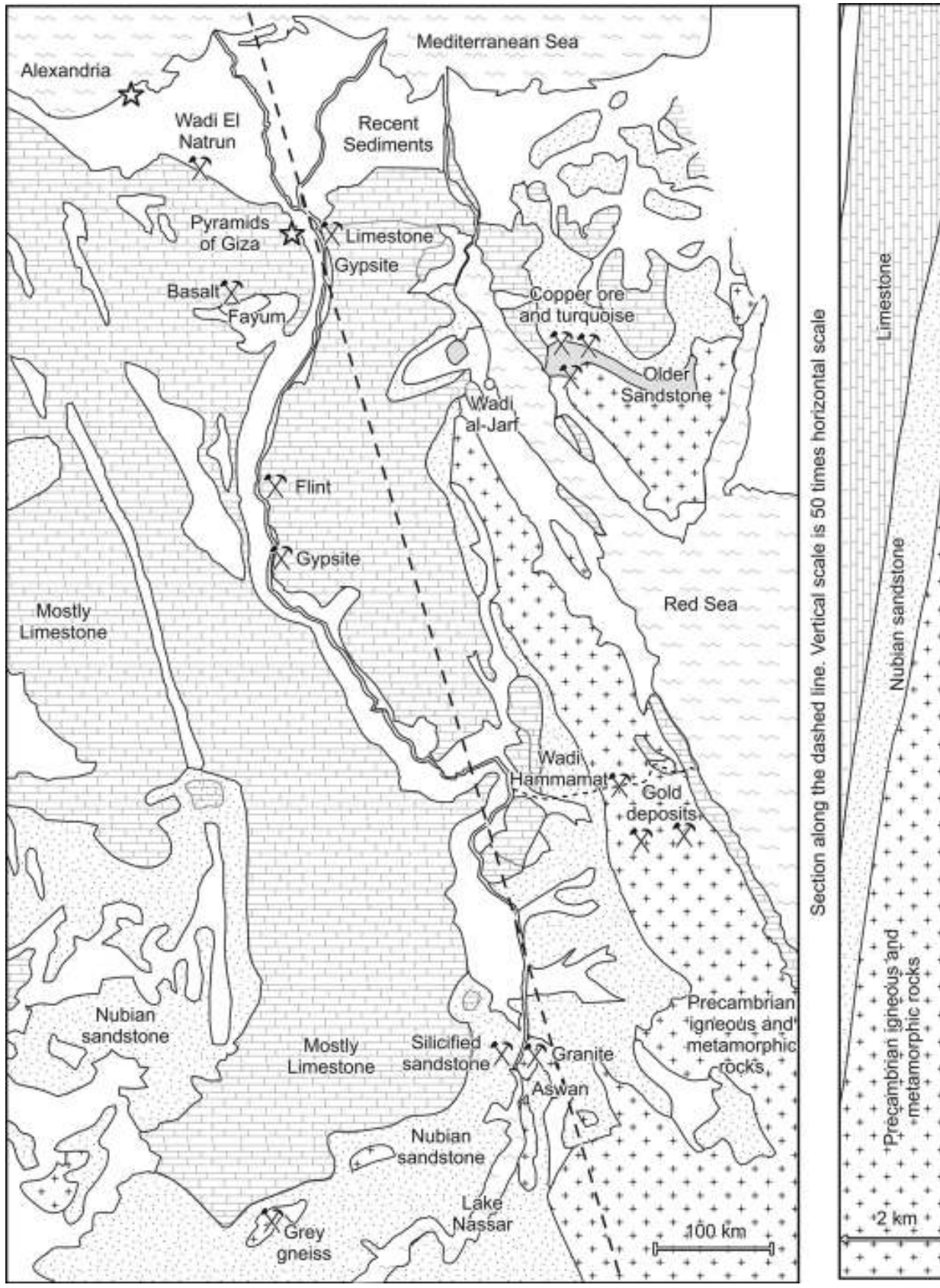


Figure 2-16: The geology of Egypt is dominated by layers of sedimentary rocks deposited on older metamorphic and igneous rocks. The vertical scale of the section is fifty times that of the horizontal scale, meaning that the layers have only a very low slope towards the north. Map by the author after "The Geological Map of Egypt," WCC 1985.

two dams have been built to exploit the power of these rapids, the last and largest being the High Dam, completed in 1970.

The next important geological layer is the "Nubian" sandstone.[59] By about 500 million years ago, the crust here had become stable and erosion had created a flat plain close to sea level. Erosion of the basement rocks produced quartz-rich sand that was blown by the wind into dunes. As the sand deposits became thicker, the lower parts were cemented, eventually making a layer of sandstone 500 to 2,000 m thick. This sandstone, which makes up the cliffs of the Nile valley near Aswan, was quarried extensively for the construction of temples and statues. Nature tends to repeat processes and this has happened here: recent weathering and erosion of the Nubian sandstone have created the sand that makes up the modern dunes of the Egyptian desert.

The Nubian sandstones, because of their porous structure, were and are an important source of potable water in places far from the Nile.[59] The water held in these rocks was originally rain that fell fifteen thousand to five thousand years ago when the climate was wetter and cooler than now. The aquifer covers a vast area of northeastern Africa and is the largest reserve of "fossil" water in the world. It naturally reaches the surface at springs, particularly along faults and at the base of cliffs, as well as in oases. In antiquity, people commonly improved access to such natural sources by digging wells, especially along trading routes. The aquifer is still exploited today using new wells drilled deep into the sandstone but it is a non-renewable resource that may not last for much longer.

And finally, there is a layer dominated by limestone that formed about fifty to five million years ago when most of the region was regularly covered by a shallow sea with abundant marine life.[59] Shells and carbonate mud accumulated on the seafloor and were slowly transformed into limestone: there, small grains dissolved in the trapped water, and calcite crystals subsequently precipitated, cementing the larger grains. In some cases, calcite was further transformed into dolomite by interaction with seawater. Limestone from this layer played an important role in the story of the pyramids.

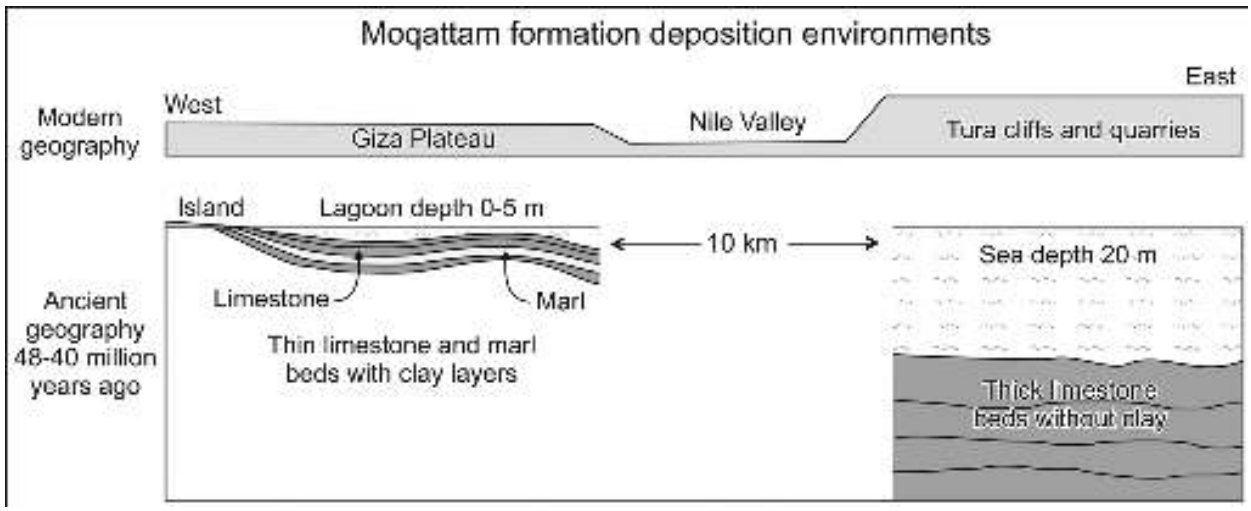


Figure 2-17: When limestones of the Moqattam formation were being deposited, most of the Giza-Tura region was covered by shallow seas. The modern geography is very different as the land has been raised and the Nile has cut a wide valley across the area. Image by the author.

The two different types of limestone that were used for the core and casing of the pyramids are quite different as they were deposited in different environments but at the same time (Figure 2-17). Both are part of the Moqattam formation, named after a hill to the northeast of Cairo (Figure 2-8).

The future site of the Giza Plateau was a shallow lagoon, home to many marine animals, now preserved as fossils, some of which have weathered out of the rock. The most common are disk-shaped shells up to 10 millimetres long that Herodotus thought were petrified lentils left over from feeding the pyramid workers, an idea that may have contributed to the myth that the pyramids were the granaries of the biblical character Joseph. At some times and in some places, the water was shallower and impurities, like clay, were washed off islands and deposited together with shells and carbonate mud in the shallow seas. These sediments were transformed into the thinly bedded limestone that was used for the core. Clay-rich layers are poorly cemented and the rock can be easily split along these layers, which can help in the quarrying of blocks but also weakens the rock and makes it more susceptible to weathering, such as is seen in the body of the Sphinx. To

the east, where the Tura cliffs now lie, the sea was deeper and swept by currents, so deposition was rarely interrupted by the influx of clay, finally yielding the thick beds of the high-quality limestone that were used for the casing of the pyramids (Figure 2-12).

Granite and Other Hard Stones

Granite was the second most important construction material at Giza, used in all the pyramids and their temples (Figure 2-5). In the Pyramid of Khufu, it formed the lining of the tomb, probably to make it more resistant to robbing, but without evident success. In the pyramids of Khafre and Menkaure, granite was also employed for the lowermost part of the casing. So much granite was used in the valley temple of Khafre that it is sometimes referred to as the "Granite Temple." In all, about ninety thousand tons went into the constructions at Giza.[61] The stone was quarried at Aswan, 850 kilometres to the south, and transported down the Nile to Giza. The combination of granite and limestone used at Giza may have symbolized the political union of the valley and the delta that figures so strongly in the iconography of ancient Egypt.[23]

To modern quarry workers, any hard rock is granite but to geologists it has a much more specific meaning: it is a rock that crystallized

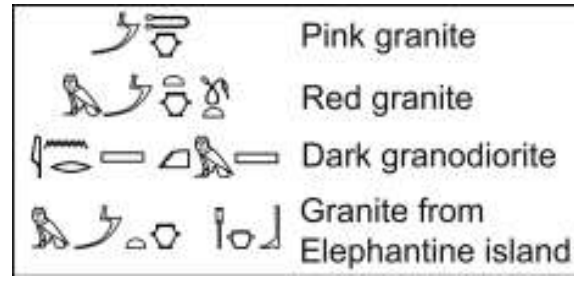


Figure 2-18: Hieroglyphs for granite and other rocks from Aswan. Image after Kelany, A., et al., 2009, "Granite Quarry Survey in the Aswan Region, Egypt: Shedding New Light on Ancient Quarrying." In *QuarryScapes: Ancient Stone Quarry Landscapes in the Eastern Mediterranean*. N. Abu-Jaber et al., editors., Geological Survey of Norway Oslo, Norway, 87–98.

from a silica-rich magma deep in the earth. Slow cooling from temperatures of about 800°C at depths of 5 to15 kilometres allowed quartz (SiO_2), potassium feldspar ($KAlSi_3O_8$), and plagioclase feldspar ($[CaAl,NaSi]AlSi_2O_8$) to form crystals in almost equal proportions that are large enough to be seen with the unaided eye. There are also lesser quantities of darker iron- and magnesium-bearing (mafic) minerals such as hornblende and biotite.

There is an important range in crystal size, colour, and mineral proportions in rocks from different parts of the Aswan quarries.[61] The rock that was most commonly used is pink to red and was a true granite, with almost equal proportions of plagioclase, potassium feldspar, and quartz, and a smaller quantity of mafic minerals. Darker rocks are sometimes called "black" granite and have a greater amount of mafic minerals. Such rock is more precisely called granodiorite and a famous example is the "Rosetta Stone."[62]

The Aswan quarries cover an area of eight square kilometres on the east bank of the Nile just north of the modern dam.[42,60,61] During the Old Kingdom, the pyramids at Giza were the most important destination for the granite from these quarries. At that time, most granite blocks were not quarried from the bedrock but cut from loose boulders, some of which were very large (Figure 2-19). The rounded surfaces of the original boulders are still preserved on the backs of some blocks used in the casing of the pyramids. These boulders were not rounded by flowing water, but by weathering in an ancient tropical environment.

The processes which lead to the creation of the rounded boulders started deep in the earth with the crystallization of granite (Figure 2-19). Subsequently, the overlying rock was eroded and the granite rose slowly to the surface. As the rocks rose in the earth, the confining pressure was reduced and the rocks cracked making joints, which can be seen in most rock outcrops. Aswan granite was exposed on the surface during the Palaeocene period (seventy-seven to thirty-three million years ago) when the climate in Egypt was hot and humid. Rainwater penetrated the joints in the granite and weathered it into a loose, gravelly material called saprolite, leaving behind rounded core

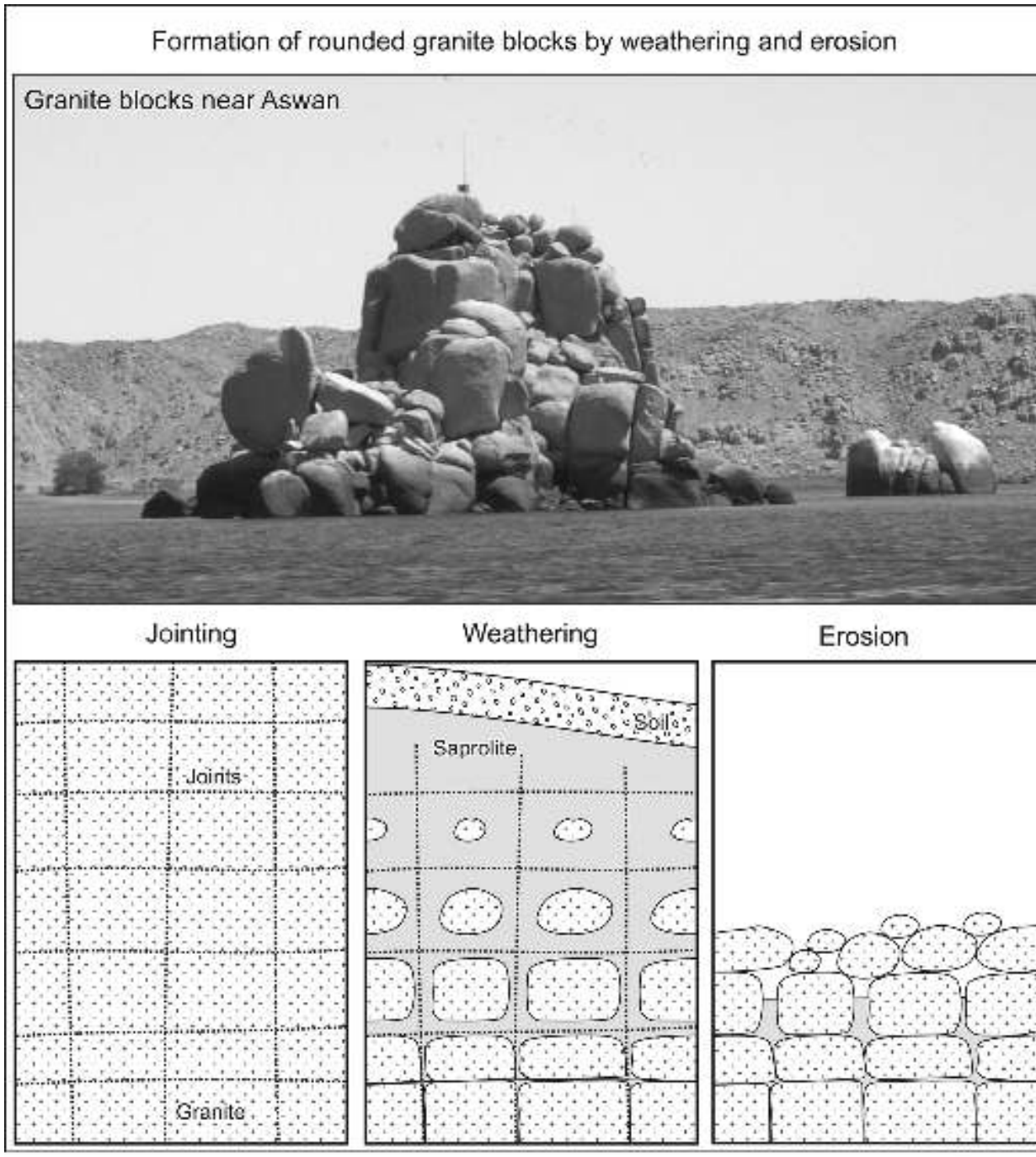


Figure 2-19: Granite boulders at Aswan were formed by weathering that started along joints (cracks), finally making rounded blocks that were subsequently exposed by erosion. Those seen here are exposed on a small island near the reconstructed Temple of Philae. Photo courtesy of the author.

blocks. Later on, erosion removed the soil and saprolite, leaving these blocks exposed and resting on solid rock.

For most purposes, granite could be obtained from boulders near the surface, but where larger blocks were needed, they had to be excavated directly from the solid bedrock. This was particularly important later on for the large obelisks and monumental statues of the New Kingdom, more than a thousand years after the Giza Pyramids.

It used to be thought that the trenches were excavated by pounding the granite surface with blocks of a dark, fine-grained, hard rock called dolerite (= diabase), but experiments have shown that it was easier if the blocks were thrown at the surface.[63,64] Angular blocks were most efficient and the stone hammers were discarded once they became rounded. The granite flaked off and the powder was then swept aside (Figure 2-20). The final shaping of the blocks was done in the same way with fine-grained stone hammers, possibly fitted with handles.

Granite is relatively easy to crush as the dominant feldspar minerals have planes of weakness, called cleavage, along which they crack easily and this process is easier if the feldspar crystals are large, as at Aswan. In contrast, the small interlocking crystals of plagioclase in the stone hammers resist crushing. Sometimes the granite was first weakened

Figure 2-20: Dolerite stone hammers ten–twenty centimetres in diameter were used to excavate granite blocks, yielding a distinctive dimpled surface seen here near the Unfinished Obelisk at Aswan. Dolerite occurs in dark-coloured dykes that were injected along cracks into this outcrop of Aswan granite. Photos courtesy of the author.

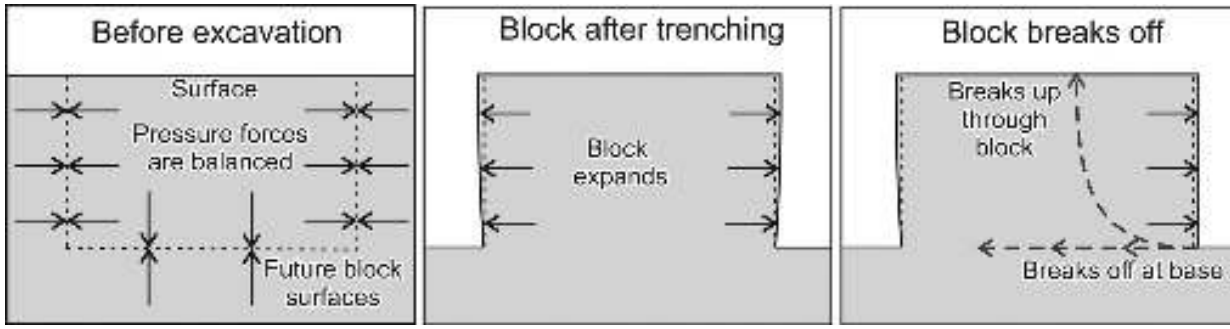


Figure 2-21: In a homogeneous, unfractured granite, the pressure on the sides of the potential block is balanced by the surrounding rocks. After the trenches have been cut, this balance no longer exists and the block expands, ideally breaking off at the base or less usefully up through the block. Image by the author.

by lighting a fire—the heat causing the mineral grains to expand and fracture, making it faster to remove material by impact.[65]

Modern experiments have shown that the process is not as slow as might be thought: an experienced worker using a 15 cm block could remove about 30 cubic cm of rock per day.[64] Hence, the trenches around the 42 metres long "Unfinished Obelisk" at Aswan could have been done in a year during daily eight-hour shifts of workers[50] (Figure 2-20).

Once the trenches were excavated, the block was no longer constrained by the surrounding rock and expanded on all sides except the base, where it was fixed to the bedrock (Figure 2-21). If the rock had existing joints (cracks), then they would have guided the direction of breakage (Figure 2-19). If the rock was intact, then the stress would be concentrated at the lower corners and a crack would develop there. Sometimes a bit of help was needed and wedges would be driven into a notch at the base of the block. However, in some cases the crack would develop in the wrong place or before the excavation was complete, making the block useless, as happened for the huge "Unfinished Obelisk." Limestone blocks were excavated in the same way, except that weaker layers in the rock made it easy for the rock to spall off along horizontal planes (Figure 2-10).

Dolerite for the stone hammers is found in the Aswan granite as sheet-like dykes formed when a magma compositionally similar to

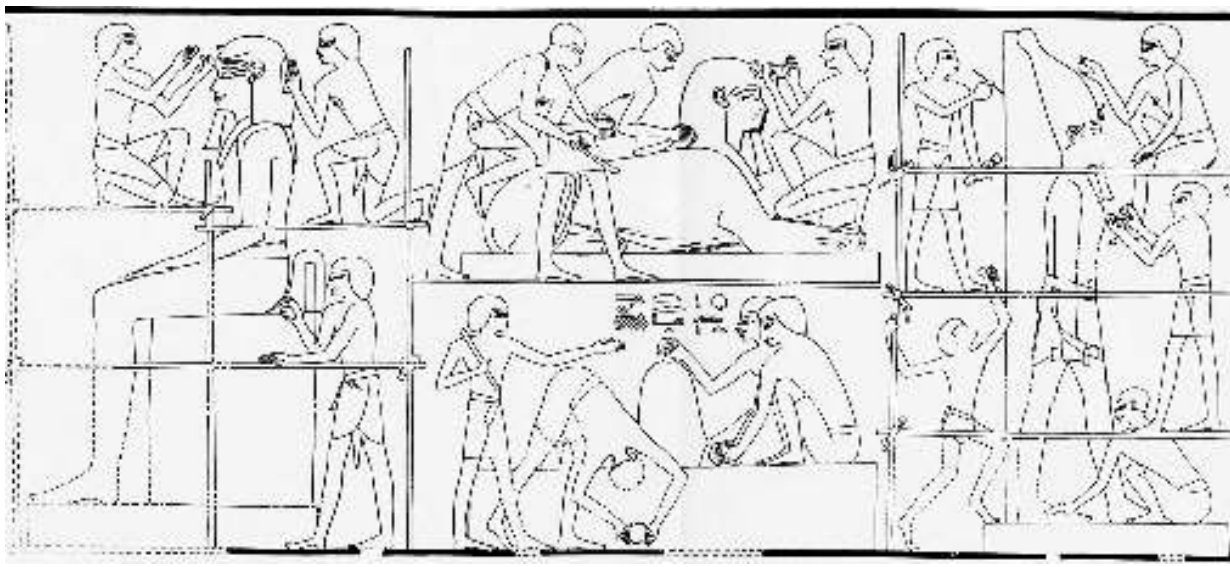


Figure 2-22: A team of sculptors are at work on two statues, a sphinx and an altar. Some are doing heavy work with round pounders/mauls, and others are using metal chisels or polishing stones with abrasives. This image was traced from the tomb chapel of *Rekh-mi-re* at Thebes, built a thousand years after the Pyramids of Giza. Davies, N.d.G., 1943, "The Tomb of Rekh-mi-re' at Thebes." *Publications of the Metropolitan Museum of Art Egyptian Expedition*. Vol. 11, Metropolitan Museum of Art: New York, NY.

basalt was injected into cracks (Figure 2-20).[63] Initially, natural blocks of dolerite were used, but later small quarries were established for this essential material.

After the granite blocks were extracted and roughly shaped with dolerite hammers, they were smoothed and polished by rubbing the surface with dolerite blocks and a slurry of angular quartz grains in water (Figure 2-22).[66] Much of this quartz was extracted from a thick vein that crops out about 3 kilometres north of Aswan, which was favoured as the crystals there are pure and more resistant to abrasion.[61] More elaborate carving was done with copper chisels, saws, and tube drills (see box 2-5: Copper Stone-Working Tools).

Another hard rock was used for statuary and bowls: gneiss[67] (Figure 2-4). This metamorphic rock was made by the action of heat and temperature on precursor rocks, in this case older igneous rocks, and is largely composed of green to black hornblende and white plagioclase feldspar. The rock is banded because it was deformed during formation deep in the crust. The proportion of the two minerals is

very variable, giving rise to a large range of names: diorite for darker examples and anorthosite for paler rocks.

The exploitation of the gneiss quarries started five thousand years ago and was active when the Giza Pyramids were built. The quarries were far from the Nile necessitating special methods for transport.[68] One-metre-high ramps at the quarries may have been used to load blocks onto amphibious rafts. These were dragged over the desert, probably lubricated with clay, to a wadi that may have flowed intermittently. From there they were dragged along the stream bed and floated across residual pools until they reached the Nile.

Transporting granite from Aswan to Giza gave rise to different challenges: the quarries were near the Nile but a huge quantity of material had to be moved downstream. Some people assume that wooden boats were used but this seems unlikely: it is not easy to load a boat with such heavy items without upsetting it, and once loaded the boat would not have been very stable. A better solution may have been to use barges made of tree trunks lashed together, bolstered with floats made of inflated animal skins.[68,69] Such a solution was used in the 19th century to float a huge Assyrian statue down the Tigris to Basra (Plate 7a) and similar barges were used there until recently. The barges could have returned from Giza to Aswan using a mast and sail to harness the dominant winds from the north. Gneiss blocks may have been moved down the Nile in the same way, perhaps on the same rafts that were used to get the stone from the quarries to the Nile.

The builders at Giza also used small amounts of basalt, a black fine-grained volcanic rock, to make pavements in some of the temples (Figure 2-23). It is thought that the dark colour of the rock symbolized the fertile black soil of the delta, and indirectly Osiris, the god of death and rebirth.[42] Basalt magma flows readily from fissures or ash cones onto the surface, commonly making long lava flows. Large basaltic volcanoes occur in places like Hawaii and Iceland, but smaller volcanoes are much more widespread, as in Egypt. One such volcano erupted twenty-five million years ago to the west of Giza (Figure

Figure 2-23: A pavement of interlocking dark basalt blocks was laid beside the Pyramid of Khufu. Photo © Per Storemyr.

2-16). In Old Kingdom times, the Haddadin lava flow was quarried near Gebel Qatrani, just north of Fayum, and the basalt used at Giza probably came from there.[70,71] Basalt is hard, difficult to trim, and not available in large blocks, so it must have had exceptional religious significance to merit its use.

Preserving the Pharaoh's Body

While the pyramid and sarcophagus were intended to protect the deceased pharaoh from external threats, the internal forces of decay were combated by mummification. Much has been written about the process, but it should be remembered that there are no descriptions

Figure 2-24: A crust of pale mineral salts called *natrun* forms in the saline lakes of Wadi El Natrun by evaporation of the water during the hot summer. Algae give the lake its pink colour. Image © Jenefer Metcalfe, The University of Manchester (2005).

of the ancient techniques related by their practitioners. However, we do know that one of the most important materials used in mummification was natrun.

Natrun ("natron" in archaeological literature) is a white powdery substance, rich in sodium carbonate, produced by evaporation of water in a series of saline lakes along Wadi El Natrun, just west of the Nile delta (Figure 2-16, Figure 2-24).[72,73] Exploitation started over six thousand years ago for use in mummification: it was packed into the body cavity to accelerate drying before decay set in. It was also a vital ingredient in glass (see Chapter 4) and Wadi El Natrun later supplied the needs of the whole Roman Empire. Finally, it was used as a detergent in the manufacture of cloth ("washing soda"). Even today, we recognize the name natrun in the modern chemical abbreviation for the element sodium, Na, via the Latin *natrium*.

Wadi El Natrun lies along a fault parallel to the edge of the delta and movements of this fault may be related to subsidence of the delta (see Chapter 8). Many saline lakes line the bottom of this closed valley, which descends below sea level. The lakes are fed by perennial springs, some underwater. This water is rich in sodium carbonate, which was dissolved from the surrounding rocks as the water passed through them. In winter, flow from the springs exceeds evaporation and the lakes fill with water, but in summer many lakes dry out and deposit salts and other minerals (Figure 2-24).[74]

Natrun is composed of many different chloride, sulphate, and carbonate minerals, and the mixture varies with the time of the year and location in the valley.[74] One of these minerals, rather confusingly called natron ($Na_2CO_3 \cdot 10H_2O$), is ironically very rare in Wadi El Natrun. You can see from the chemical formula that it contains a lot of water, and would not have been the best material for drying out a mummy. The most common sodium carbonate mineral here is trona ($Na_3[CO_3][HCO_3] \cdot 2H_2O$), which contains much less water. The greatest concentration of this mineral is in the crusts formed in the hottest part of the summer. Mummification did not need pure trona, but for making glass the raw material would have needed purifying by removal of chloride and sulphate minerals. This would have been done by dissolving the salts in water and carefully drying the solution so that the different minerals were precipitated sequentially.

Another vital ingredient in mummification at the time of the Giza Pyramids was resin from conifers and pistachia genera trees, which was used to treat the body directly and also poured between the mummy and the coffin. With time it oxidized to a black tarry substance from which the word "mummy" is derived—"*mūmiyyah*" is the Arabic word for bitumen. As mummification became more popular, a shortage of resin created a demand for a substitute: bitumen. This was not sourced in Mesopotamia, where bitumen from springs was so important for construction (see Chapter 3), but from the Dead Sea where it floated to the surface as huge blobs (see Chapter 3, box 3-5: Dead Sea Bitumen and the Nabateans).[75]

The Pyramids since Antiquity

Although the pyramids of Giza are more complete than the other Wonders, they are not as they were when the pharaohs were entombed (Plate 3a). The rich grave goods were all robbed in antiquity, probably during a period of instability about three hundred years after the construction of the pyramids. Herodotus, writing in the 5th century BCE, mentions that the entrance to the tomb of Khufu was open at that time.[53] Sometime later, one or more earthquakes brought down the original entrance to the Pyramid of Khufu and buried it in rubble: a possible culprit was the huge event of 365 CE (see Chapter 8). We know that the portal was completely hidden in 820 CE when the Caliph Al-Ma'mun ordered the excavation of a new entrance to pursue his search for hidden treasure—this entrance lies just under the original one and is that used by tourists today.

In the 12th century CE, Sultan Al-Aziz Uthman tried to demolish the pyramids as he considered that they were "instruments of idolatry." He started with the smallest, but the project turned out to be very difficult and was abandoned after eight months of work, leaving an ugly gash on the north side of Menkaure's Pyramid (Figure 2-25).

Some early explorers also damaged the pyramids with explosives. In the 1830s, Richard Howard Vyse blasted open the Pyramid of Menkaure and found the burial chamber.[33] He also opened the chambers above the main burial chamber in the Pyramid of Khufu, where he found rough limestone blocks that still had their quarry marks painted in red ochre, including the name of the pharaoh Khufu—the only place that it has been observed in the pyramid.

However, the most evident change since antiquity is the loss of the outer casing of high-quality limestone and the subsequent erosion of the inner core blocks. The casing stones were still almost intact when the Persian writer Abd al-Latif visited the pyramids in 1203 CE.[76] Removal of casing blocks for construction in Cairo must have started in early medieval times and by 1639 CE John Greaves wrote

Figure 2-25: The north side of Menkaure's Pyramid has a gash that is the result of a mediaeval attempt at demolition. The remains of the granite casing can be seen at the base of the pyramid to the right. Photo courtesy of the author.

that the Pyramid of Khufu had been completely stripped, as had most of the south side of the Khafre Pyramid.[77] Now all that remains of the casing is at the top of the Pyramid of Khafre (Figure 2-3).

Removal of casing blocks may have been facilitated by a major earthquake in 1303 CE, centred near western Crete, which also helped bring down two of the other ancient wonders: the Pharos and the Mausoleum (see Chapter 8).[78] It also caused very extensive damage to mosques and other buildings in Cairo, partly because the loose river sediments in the Nile valley tend to amplify seismic waves and increase their destructive power.[79] Although no records show that it affected the pyramids, it is certainly possible that the shaking could have loosened some of the casing blocks and caused others to fall—the

wavelength of some seismic waves are close to the dimensions of the pyramid and could have caused it to ring like a bell. There would have been a ready market for these stones for the reconstruction of Cairo after the earthquake, and active quarrying of intact casing blocks may have started soon after. The looting only finished when it was cheaper to quarry new stone from the cliffs to the east than to scale the pyramids.

Once the casing blocks were removed, the inner, lower-quality limestone blocks began to erode, largely from salt crystallization. The large temperature difference between night and day means that dew condenses on the rocks at night, and is drawn into the rock by capillary action, dissolving salts such as gypsum ($CaSO_4 \cdot 2H_2O$) from the mortar used to fill in gaps between the blocks and other salts blown in from the desert.[80] When the sun comes up, the water evaporates and salts crystallize just below the surface, flaking off grains of limestone. Over time, this can remove significant amounts of rock, giving the rough surface that we see today (Figure 2-11).

The Sphinx has also been eroded very extensively, especially the body, which was carved from a marly limestone layer that was weaker than the layer that comprises the head (Figure 2-2). In addition to the weathering processes described earlier, the body of the Sphinx is close to the water table, below which the rocks are saturated in water. Moisture is carried up into the statue by capillary action, where it evaporates and crystallizes salts just below the surface, which flake off the outer skin of the rock. This problem was evident over two thousand years ago, in Ptolemaic times, when extensive repairs to the base of the statue were carried out (Figure 2-6). Since the construction of the Aswan High Dam enabled year-round irrigation, the water table has risen and there is now significantly more erosion. An additional problem is water leaking into the subsurface from municipal aqueducts and sewers serving the vast, growing suburbs west of the pyramid plateau.[45] The head has largely escaped damage as it was cut from a limestone bed that is better cemented and is also too high up to be wetted by groundwater.

It is difficult not to conclude that the Pyramids are the greatest of the ancient wonders. They are the oldest, the largest, and the only ones to survive in a recognizable form. They are still a major tourist destination, as in antiquity, even though the view from the site is now dominated by Cairo's suburbs. Although the archaeological remains are now much better protected than in the past, a new threat has emerged: the stone itself is attacked by air pollution from nearby Cairo. Tombs and other underground structures are also affected by rising groundwater and pollutants brought in by tourists, including their breath. Perhaps the only real solution to the preservation of the monuments is the development of virtual tourism.[24]

3

The Gardens of Mesopotamia

The Gardens

The *Hanging Gardens*, more accurately translated as terraced gardens, are the most enigmatic of the Ancient Wonders (Figure 3-1). For ancient writers, they seemed to be so far away, one thousand kilometres from the Mediterranean, that anything could be said about them with little chance of criticism. Although the traditional view is that the gardens were set in the walled city of Babylon during the 6th century BCE, there is growing support for the idea that the gardens were at Nineveh in the 7th century BCE.[94] Although the zenith of Nineveh predates that of Babylon by more than a hundred years, I will talk about them in reverse chronological order, to respect tradition and to emphasize that the walls of Babylon were included in early compilations of the world wonders.

There are five ancient descriptions of the Gardens and the most complete was by the Greek writer Diodorus Siculus, who compiled it around 60–30 BCE from now-lost sources.[95,96] "There was also beside the acropolis, the Hanging Gardens, as it is called, which was built . . . [by a] Syrian king to please one of his concubines; for she, they say, being Persian and longing for the meadows of her mountains, asked the king to imitate, through the artifice of a planted garden, the distinctive landscape of Persia. The park extended four plethra [120 metres] on each side, and since the approach to the garden sloped like

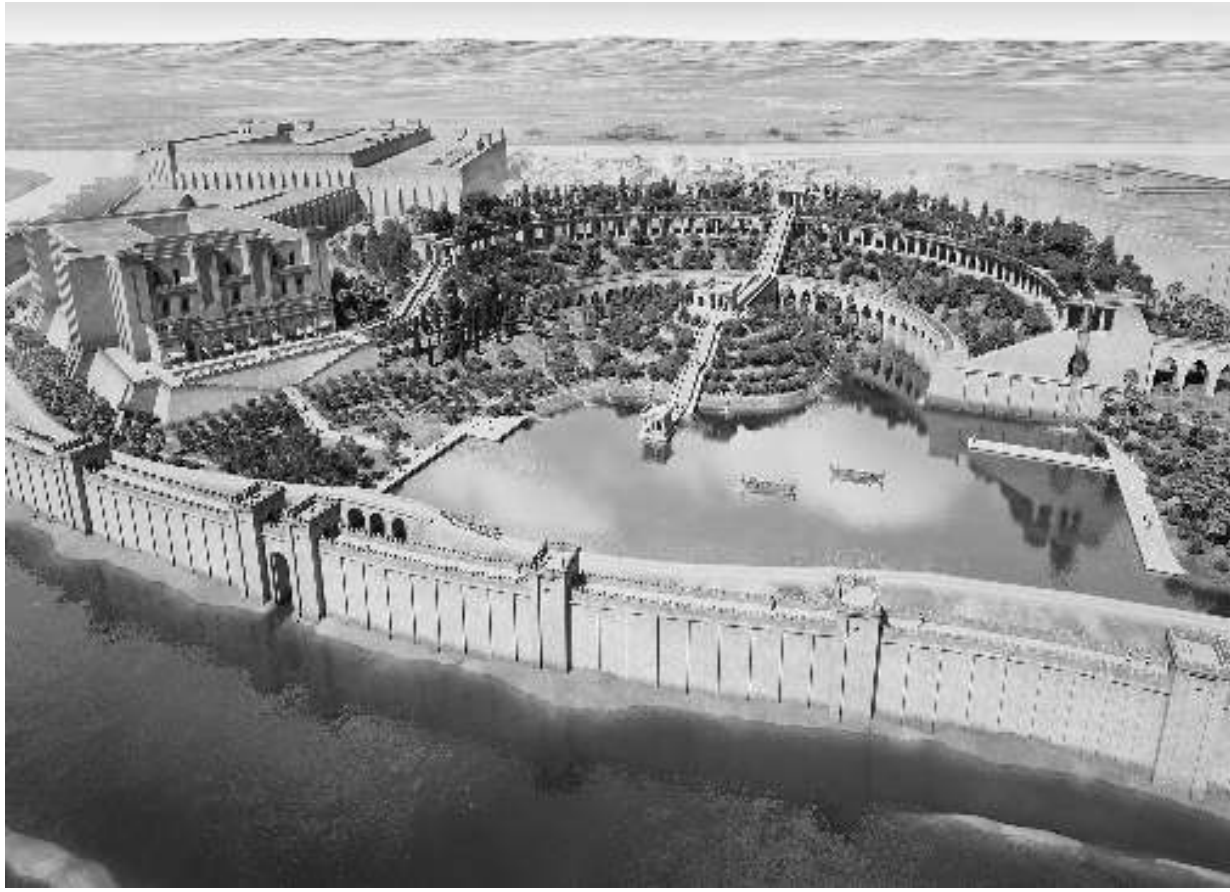


Figure 3-1: A terraced garden and artificial lake are envisaged here next to the Palace of Sennacherib at Nineveh. Many rulers in ancient Mesopotamia built gardens near their palaces and ancient descriptions of the wondrous *Hanging Gardens of Babylon* may be a conflation of several different royal playgrounds projected onto a well-known city. Image © Josep R. Casals.

a hillside and the several parts of the structure rose from one another tier on tier, the appearance of the whole resembled that of a theatre. When the ascending terraces had been built, there had been constructed beneath them galleries which carried the entire weight of the planted garden and rose little by little one above the other along the approach; and the uppermost gallery, which was fifty cubits high [25 m], bore the highest surface of the park, which was made level with the circuit wall of the battlements of the city. Furthermore, the walls, which had been constructed at great expense, were twenty-two feet thick [7 m], while the passageway between each of the two walls was ten feet wide [3 m]. The roofs of the galleries were covered over with beams of stone sixteen feet long [5 m], inclusive of the overlap,

and four feet wide [1.3 m]. The roof above these beams had first a layer of reeds laid in great quantities of bitumen, over this two courses of baked brick bonded by cement, and as a third layer a covering of lead, to the end that the moisture from the soil might not penetrate beneath. On all this again earth had been piled to a depth sufficient for the roots of the largest trees; and the ground, which was levelled off, was thickly planted with trees of every kind that, by their great size or any other charm, could give pleasure to the beholder. And since the galleries, each projecting beyond another, all received the light, they contained many royal lodgings of every description; and there was one gallery which contained openings leading from the topmost surface and machines for supplying the garden with water, the machines raising the water in great abundance from the river, although no one outside could see it being done."

The major problem with this wonderfully detailed text is that neither the city nor the king is named. The association of the gardens with Babylon comes from Josephus, a Roman-Jewish historian writing in the 1st century CE who quoted an earlier source that identified the king as Nebuchadnezzar II of Babylon (634 to 562 BCE).[96] This king was well known as the ruler whose army sacked Jerusalem and deported the Jews to Babylon, which is why they regarded the city as the centre of evil: "Babylon the great, mother of harlots and of earth's abominations" (the biblical Book of Revelations, 17:5). Babylon also appeared in another context: early lists of the Seven Wonders included the Walls of Babylon, later supplanted by the Pharos of Alexandria.

Babylon lay at the heart of Mesopotamia, the broad valley dominated by Euphrates and Tigris Rivers, which flow from the mountains of southern Turkey to the Persian Gulf (Figure 3-2).[97–99] The geography of this region has changed significantly in geologically recent times, with important cultural consequences. Rising sea levels caused by the melting of distant glaciers first filled the Persian Gulf and then advanced up the valley of the Euphrates and Tigris Rivers until the sea reached its maximum extent about eight thousand years ago (Figure 3-2).[100] Shortly after, the deltas of the two rivers advanced

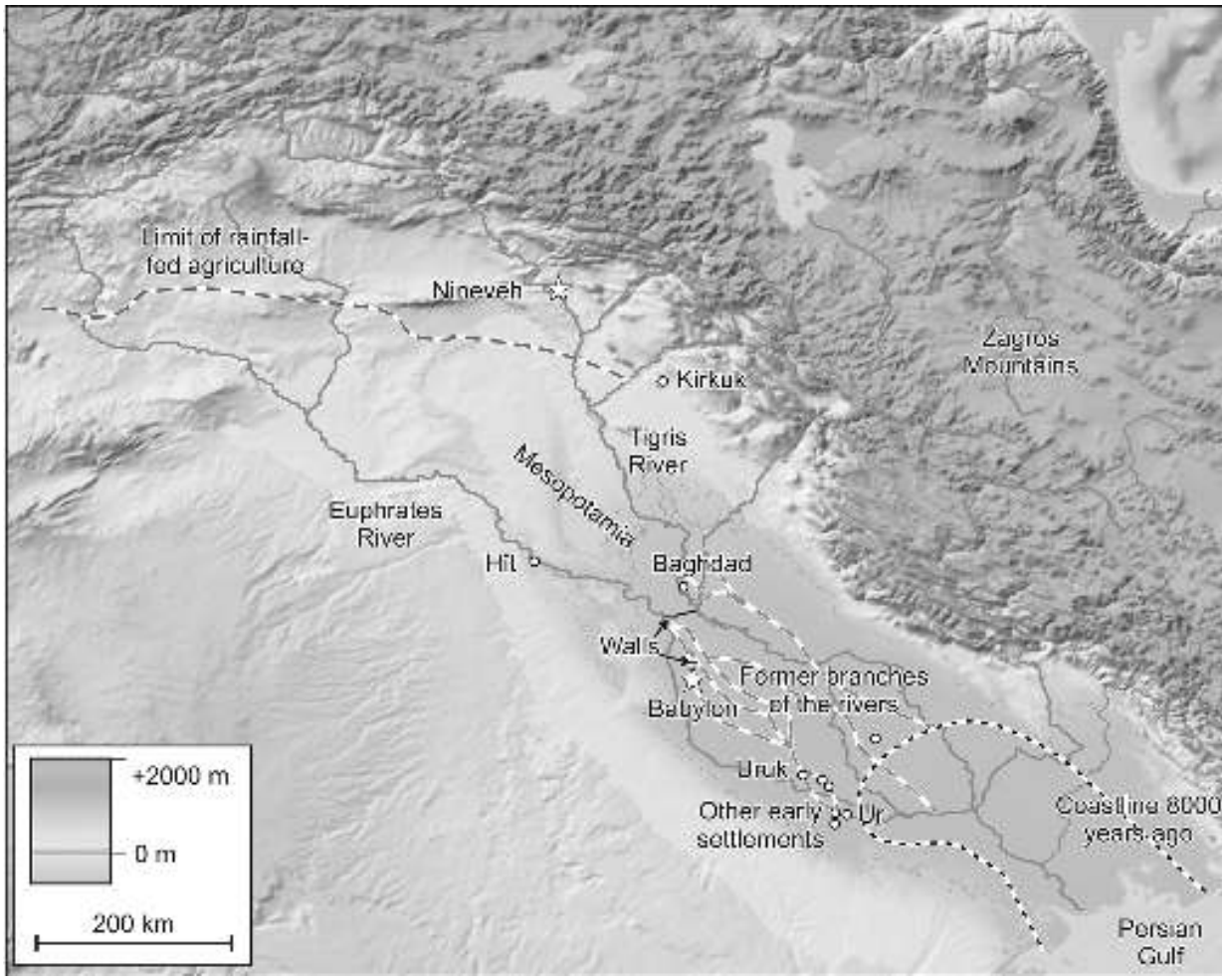


Figure 3-2: Mesopotamia was defined by the wide valley of the Euphrates and Tigris Rivers. Below Baghdad, the two rivers meandered across the plains and could not always be distinguished. Map by author after Amante, C. and B.W. Eakins, 2009, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24; Finkel, I.L. and M.J. Seymour, 2008, *Babylon*. Oxford University Press: Oxford; New York; Wilkinson, T.J., 2003, *Archaeological Landscapes of the Near East*. University of Arizona Press: Tucson.

rapidly into the shallow waters of the gulf making new, well-watered, fertile land, an environment also seen at Ephesus (see Chapter 6). It was in this ecologically favourable area that the first cities in the world came into being, such as Uruk, the setting for the oldest epic poem, the Epic of Gilgamesh, and Ur (see box 6-6: Sea Level and Cultural Developments). Settlement of the area was so successful that population pressure forced people upstream, leading to the development of cities farther from the coast, such as Babylon.

Babylon was founded 4,400 years ago at a key location beside the Euphrates Rivers and not far from the Tigris River, and soon became the most important settlement in central Mesopotamia (Figure 3-2). Indeed, it was known as the place where one of the earliest legal systems was recorded, including the first building code: "If a builder builds a house for a man and does not make its construction firm and the house which he has built collapses and causes the death of the owner of the house, then that builder shall be put to death."[98]

The Babylon of Nebuchadnezzar II (reigned 605–562 BCE) was a huge city, rebuilt after having been razed in 689 BCE by the Assyrian king Sennacherib, whom we will encounter later in the story of the gardens.[98,104] The inner city had a somewhat modern plan, with a grid of streets laid out on either side of the river and surrounded by a wall (Figure 3-3; Plate 4b).[101–103] A much larger outer wall on the east side defended the city from its traditional enemy Assyria. The walls were a total of 18 kilometres long, up to 25 metres wide, and had a core of mud brick, possibly faced in places with fired bricks set in bitumen. The gates were made of baked bricks, some of them glazed in bright colours (Plate 5a; Plate 5b). Herodotus speaks of 89 kilometres of walls, but this must have included defensive walls that Nebuchadnezzar built north of Babylon, one of which was said to run for 50 kilometres from the Euphrates to the Tigris (Figure 3-2).[98]

Nebuchadnezzar II ordered the construction of many wonderful buildings in the city, commonly built of mud brick, faced with stucco or fired bricks. There were temples to the pantheon of Babylonian gods and at its centre the great Etemenanki ziggurat, perhaps the inspiration for the biblical *Tower of Babel*, which was sacred to Marduk, the most important of their gods (see box 3-3: Lugalakia—God of Underground Water). In the northern part of the city, Nebuchadnezzar built a vast palace between the magnificent Gateway of Ishtar, the Processional Way, and the river (Figure 3-3). The palace may have included royal gardens, but where? Attention was initially concentrated

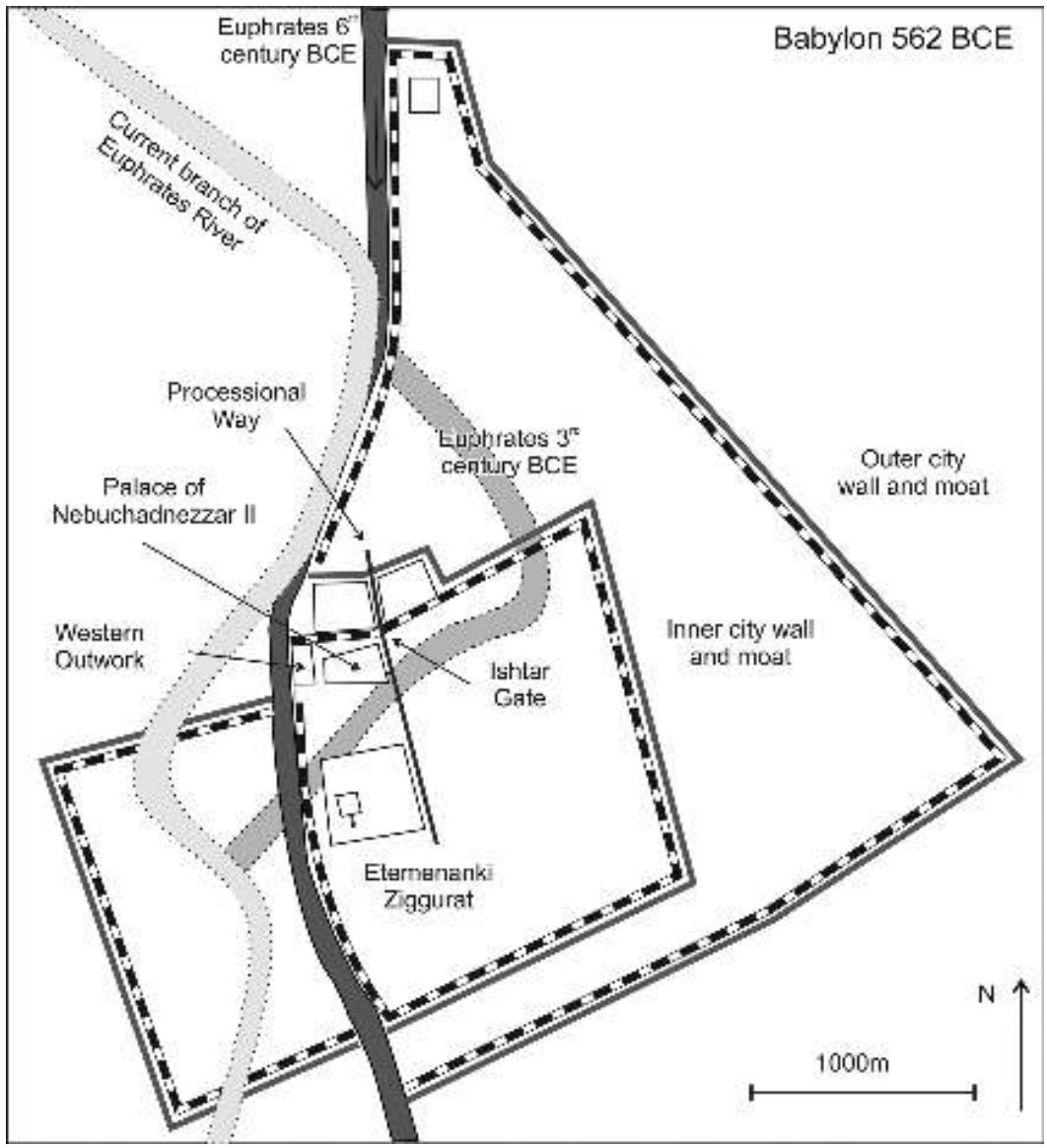


Figure 3-3: In 562 BCE, Babylon was a vast city protected by two sets of walls and bisected by the Euphrates River. By the third century BCE, when Alexander the Great died here, the river had shifted to the east, separating the ancient palace and ziggurat. Since that time, a branch of the river has meandered westwards across the ancient city. Map by author after Amante, C. and B.W. Eakins, 2009, ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24; Finkel, I.L. and M.J. Seymour, 2008, *Babylon*. Oxford University Press: Oxford; New York; Wilkinson, T.J., 2003, *Archaeological Landscapes of the Near East*. University of Arizona Press: Tucson.

on a small building in the northeast corner of the palace that was made of limestone. There are no outcrops near Babylon and the limestone must have been transported large distances. It was first suggested that this expensive building may have been the foundation of the gardens, but it is now believed to have been a treasury. Another possibility is the Western Outworks, a large building along the riverfront, but again, evidence for gardens there is not strong (Figure 3-3; Plate 4b).[101–103]

As I mentioned before, some doubt that the gardens were at Babylon at all.[94] Nebuchadnezzar II boasted of his military and cultural achievements but never mentioned gardens. In addition, there is no mention of the gardens in the writings of normally reliable authors such as the Greek historian Herodotus. This has led to the idea that the gardens may have been constructed seventy years earlier at Nineveh, then the capital of the Assyrian Empire.[106] There seems to have been much confusion between Babylon and Nineveh amongst the writers of the classical world, as both were far away and exotic.[107] For some writers, the names referred to people, not cities, which increased the confusion as rulers captured and moved whole populations from one city to another.

The Assyrian Empire emerged in the 10th century BCE from northeastern Mesopotamia, close to the Zagros Mountains, and at its zenith included all of Mesopotamia, northern Egypt, and southeast Turkey (Figure 3-2). When Sennacherib became king in 705 BCE, he moved the capital a short distance from Dur-Sharrukin (now Khorsabad) to Nineveh (Ninua), the cult city of the goddess Ishtar, adjacent to the modern city of Mosul.[106] Nineveh was already old at that time, having been founded in the third millennium BCE. The original settlement was strategically located on a small peninsula at the confluence of the small Khosr River and the Tigris River, which probably ran just to the west at that time (Figure 3-4).[105] Sennacherib expanded the city considerably and surrounded it by stone walls 12 kilometres long, further protected by a moat fed by canals. He built a huge palace on a hill now called Kuyunjik (*Sheep Hill*). This was a

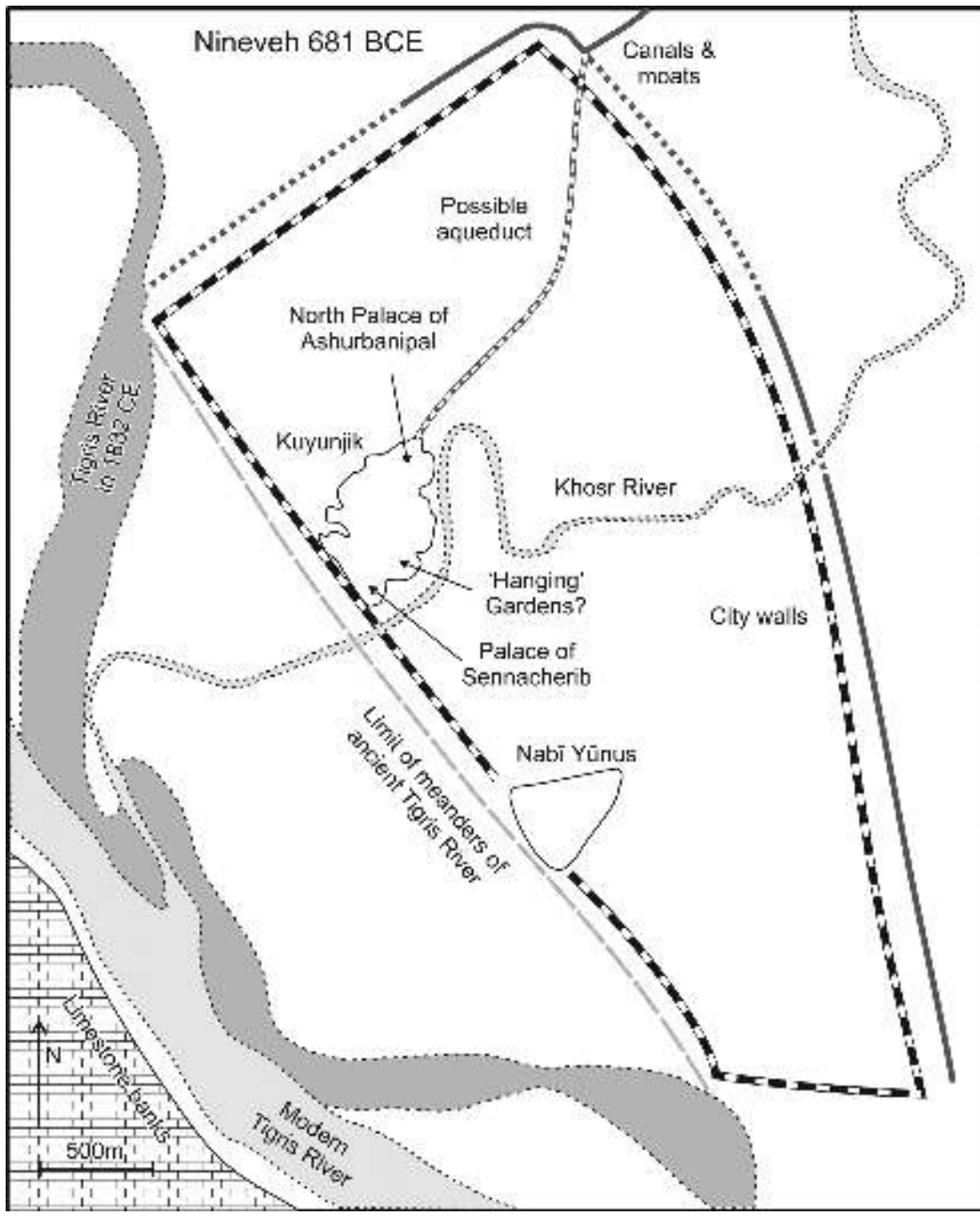


Figure 3-4: In 681 BCE, at the end of the reign of Sennacherib, Nineveh covered a huge area and may have been the largest city in the western world. The site was almost flat except for two low hills, one now called Kuyunjik, which was the location of the palace and royal gardens; and the other Nabī Yūnus, named after the tomb of Jonah, the story of whose exploits inside a whale, recounted in both the Bible and the Koran, was set some fifty years before the rule of Sennacherib. The Tigris has meandered across its flood plain and may have run close to the walls at the time of their construction. Map by author after Jones, F., 1854, "Topography of Nineveh, Illustrative of the Maps of the Chief Cities of Assyria; and the General Geography of the Country Intermediate between the Tigris and the Upper Zab." *Journal of the Royal Asiatic Society* 15: 297–396.

'tell,' a mound largely made of the accumulated remains of thousands of years of construction and decay of mud-brick buildings (Plate 6a). The original settlement may have been located on a low natural hill, similar to those a few kilometres to the north and west, now concealed within the tell.

The palace was vast, with over seventy rooms. Huge statues of human-headed winged bulls, called *lamassu*, flanked many of the doorways, similar to those from earlier palaces, and the corridors were lined with over 3,000 metres of carved alabaster, detailing the conquests and achievements of the king (Figure 3-5).[108–112]. One panel depicts his siege of the Judean city of Lachish and was the first archaeological confirmation of an event in the Bible. The inscription on another panel reads: "I raised the height of the surroundings of the palace, to be a wonder for all peoples. I gave it the name: Palace Without Rival. A high garden imitating the Amanus Mountains [Nur Mountains, south-central Turkey] I laid out next to it, with all kinds of aromatic plants." This phrase echoes the "Wonders of the World" and mentions a garden resembling mountains that I will talk about later.

Sennacherib's building account survives and describes the origin of some of the stone used in his palace originated, as well as the uses of more exotic types of stone (see box 3-1: Sennacherib's Exotic Stones),[110,114] He mentions how his predecessors quarried stone for the *lamassu* at Tastiate, probably on the west bank of the Tigris south of Nineveh (Figure 3-10). This site was not ideal, as it was only possible to transport stone across the Tigris during spring floods. Sennacherib credits divine inspiration for his choice of new quarries at Balaţai. We don't know where this was exactly, but it may have been opposite Eski Mosul on the east bank of the Tigris, or perhaps further upstream at Jikan Tell, now submerged beneath the Mosul Reservoir (Figure 3-10). This site was certainly more convenient as it not necessary to move the blocks across the Tigris River, just by land, which could be done at any time of the year. The rock at both sites is a nodular alabaster that I'll describe later.

Figure 3-5: Three-metre high human-headed winged bulls (*lamassu*) and lions made of alabaster stood beside gates and doorways in Sennacherib's Palace. Unfortunately, most are now severely damaged or destroyed. Gadd, C.J., 1936, *The Stones of Assyria; the Surviving Remains of Assyrian Sculpture, Their Recovery, and Their Original Positions*. Chatto and Windus: London.

An outstanding series of carved alabaster panels from the palace illustrates the extraction and transport of stone for the *lamassu* (Figure 3-6, Figure 3-7).[113] Sennacherib does not mention the stone that was used for the panels, presumably because he felt that it was not remarkable or worthy of his royal comments. Most of these panels were made

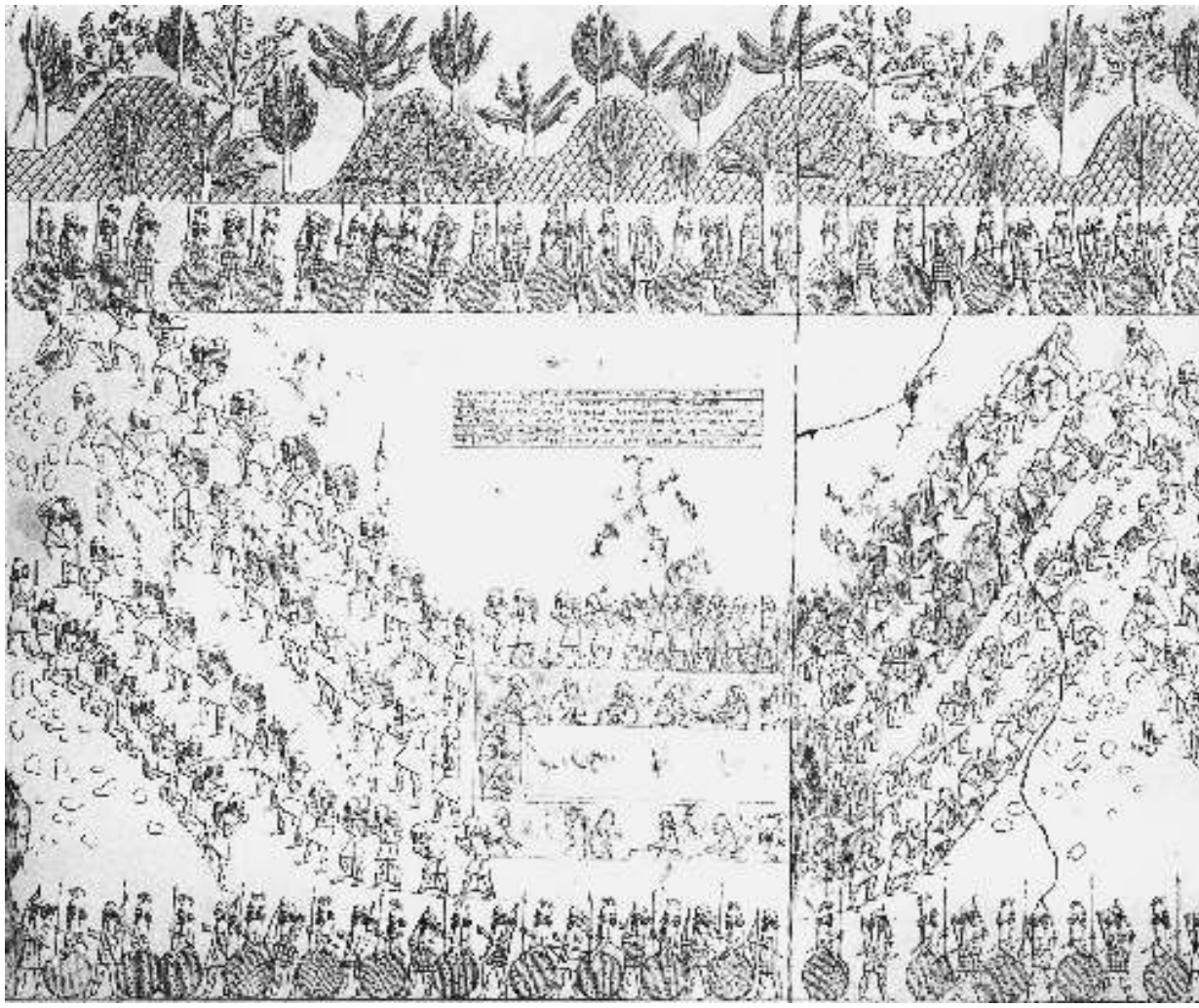


Figure 3-6: This wall panel shows a quarry at Balaţai where men rough out a block for a huge statue while others remove the waste. The workers were enslaved prisoners of war and the soldiers were there to prevent them from escaping. At the top, there are pine, fig, and pomegranate trees as well as grapevines. Such panels were originally painted in bright colours. Layard, A.H., 1853, *A Second Series of the Monuments of Nineveh; Including Bas-Reliefs from the Palace of Sennacherib and Bronzes from the Ruins of Nimroud. From Drawings Made on the Spot, during a Second Expedition to Assyria*. J. Murray: London.

from a uniform medium-grained alabaster visually different from that used for the *lamassu*. Quarries for the panels have not been found, and the rock may have been simply extracted from numerous outcrops in the region.

The gardens of Sennacherib may have been built to the northeast of his palace, terraced into the slopes that descended from the top of the tell to the Khosr River.[94,115] There is an image of such a garden in

Box 3-1 Sennacherib's Exotic Stones

Sennacherib's accounts of his construction projects mention the uses and qualities of rocks from exotic, distant places.[110] A fossiliferous limestone from Mount Nippur (near Cizre, Turkey) was used for some relief panels and resembled "mottled barley or cucumber seeds." It was also "valued for pendants, as a charm-stone efficacious for obtaining acceptance when speaking, for making bad weather pass by, and to keep diseases from attacking a person." A limestone breccia from western Assyria was used to make large stone vessels and appeared like "the wings of a dragonfly." It was "effective for assuaging throbbing in the temple and, as a charm-stone, it brings joy to the heart and happiness of mind." The Assyrians thought that illnesses were caused by ghosts and used a wide range of other rocks and minerals, many unidentified, for treatment.[143] Some materials were powdered and added to other ingredients for internal medicine whereas others were worn as amulets.

a panel excavated from the North Palace at Nineveh (Plate 6b), which was built by Ashurbanipal (668–631 BC), the grandson of Sennacherib. This image has been used to reconstruct the gardens (Figure 3-1). If the garden was created by his grandfather, then it would have been well established by his time. This image shows irrigation water entering the garden on the right along the arches of an aqueduct and flowing down naturally along channels. This model is supported by excavations that revealed an aqueduct with pointed arches and canals which could have been used to bring water to the palace mound. In the panel, the garden appears to extend upwards from the canal and Sennacherib mentions hidden devices that raised water to the highest parts of the garden. These devices may have been *Archimedes*'s screws, perhaps powered by the flow of water in the channel itself (see box 3-2: Water-Lifting Technology).[94,115] We will never know definitively the where and when of the gardens and is likely that more

Figure 3-7: This wall panel shows how the statues, each weighing up to fifty tons, were transported from the quarry to the palace. The statue was put on a sledge and workers at the back lifted it with a lever, while four teams of men dragged it forwards. In the bottom left, a shadoof is being used to raise water to fill a canal, perhaps to lubricate the sledge with clay-rich mud. Layard, A.H., 1853, *A Second series of the Monuments of Nineveh; Including Bas-Reliefs from the Palace of Sennacherib and Bronzes from the Ruins of Nimroud. From Drawings Made on the Spot, during a Second Expedition to Assyria*. J. Murray: London.

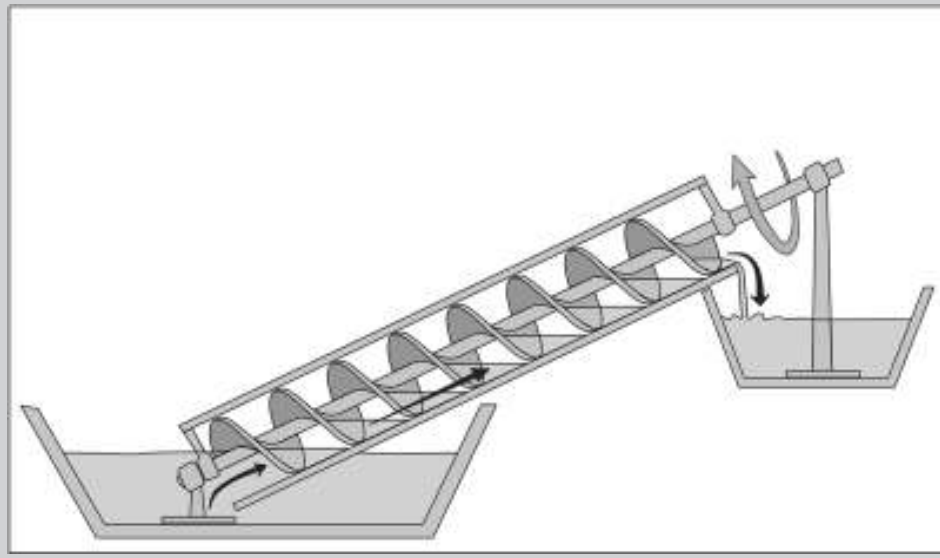
than one Mesopotamian ruler had remarkable royal gardens that may have been conflated in stories and accounts relayed to the far-off Mediterranean world.

We should perhaps be wary of imposing a modern view of garden life. In one panel from the North Palace of Ashurbanipal, the king is taking refreshments while listening to music with his wife amid luxuriant trees, from one of which hangs the severed head of an enemy (Figure 3-8)!

The great cities and gardens of ancient Mesopotamia testify to its standing as one of the cradles of world civilization. The cultural development of this region was especially favoured by local and regional geological forces, which created both its landscape and the necessary natural resources.

Box 3-2 Water-Lifting Technology

Rivers, canals, and ditches are great ways to distribute water but unless the watercourse is higher than its surroundings, water must be lifted to irrigate fields and gardens. Many methods have been developed—one of the oldest and most widespread methods is the shadoof (shaduf) or sweep, which consists of a bucket tied onto a counterweighted beam.[144] The bucket is pulled down, filled with water, allowed to rise, and finally emptied at a higher level. The success of such a simple system is that it is easier to pull something down than it is to lift it. This mechanism is easy to build and operate but is difficult to power other than by humans. It also operates intermittently rather than continuously.



Rotation of the water screw raises water to fill a higher reservoir. Image by the author.

The description of the gardens by Diodorus Siculus mentions the use of concealed machines to raise water to the highest parts of the garden and the famous *Garden* panel from Nineveh shows an aqueduct entering at a mid-level, again necessitating some water-lifting technology (Figure 3-8). Many mechanisms have been devised to overcome these limitations, but the one with perhaps the oldest pedigree is the "water-screw."[145] This is a water-tight, hollow spiral made of wood or metal, that raises water continuously as it is rotated. It is commonly attributed to Archimedes, the 3rd century BCE Greek scientist and inventor, but it is likely that he just

described or popularized the device. It has many advantages as it does not have any valves to clog up and is still used today for that reason. Although it has been suggested that such screws were powered by the flow of water in the channel, it is more likely that the screws would have been driven by slaves stepping on boards fixed to the barrel.

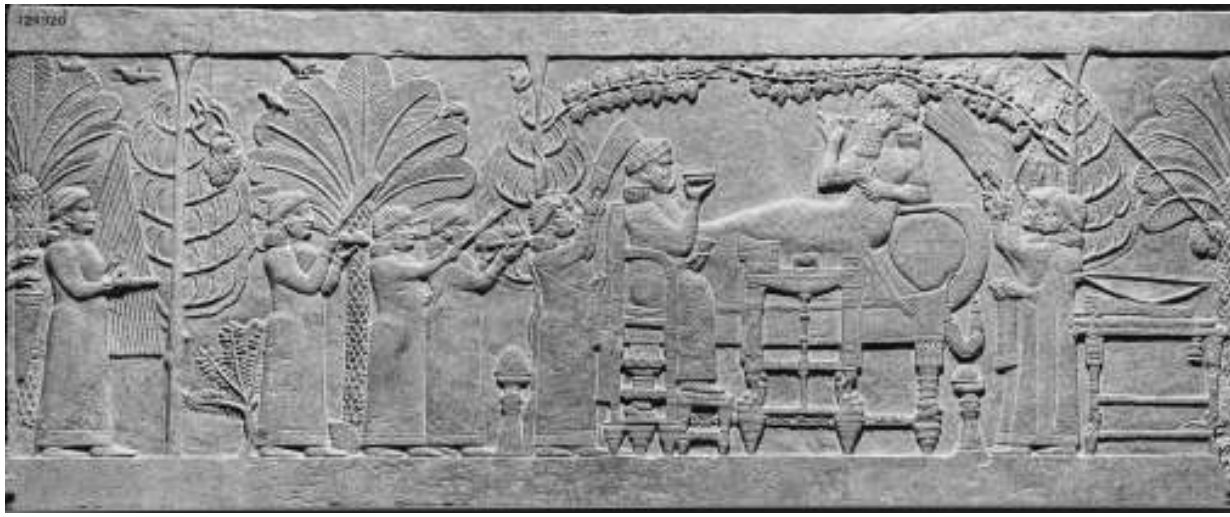


Figure 3-8: This wall panel from the Palace of Ashurbanipal at Nineveh shows the king and queen relaxing in a garden. Photo © Allan Gluck / Wikimedia Commons CC BY 4.0.

Geology of Mesopotamia

The Mesopotamian valley, part of a huge basin 1,500 kilometres long that continues to the southeast under the Persian Gulf, lies to the southwest of the Zagros Mountains in Iran (Figure 3-9). Both basin and mountains have formed in response to the northward movement of the Arabian Plate where it encounters the Eurasian Plate: the collision has thickened the earth's crust and forced up the Zagros Mountains. The basin formed in front of the mountains partly because the crust there was pushed down under them and partly because the extra weight of the mountain chain depressed the whole area (Figure 3-9). The process of convergence continues today: The

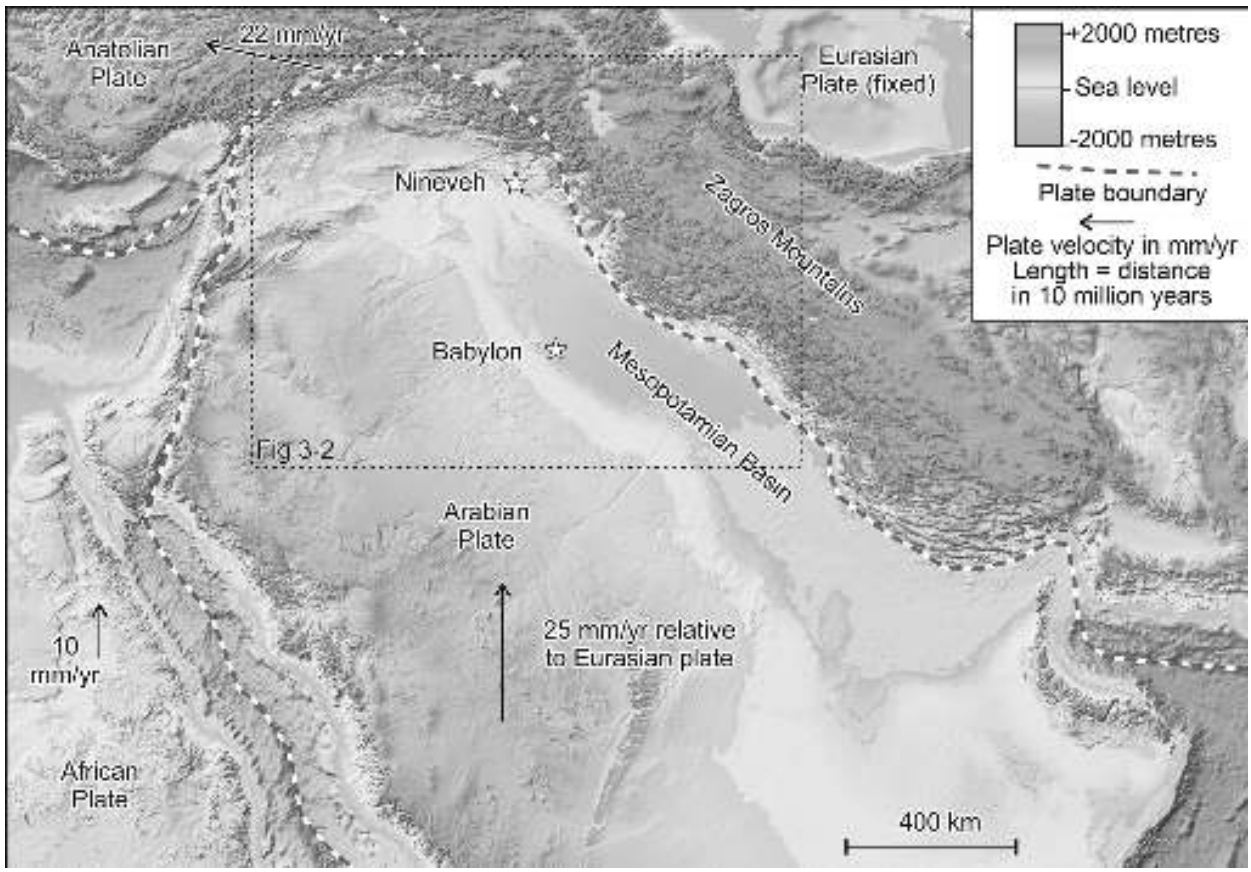


Figure 3-9: Movements of tectonic plates have strongly influenced the landscape of Mesopotamia and the surrounding region. The Arabian Plate, moving northwards towards the Eurasian Plate and compressing the crust near the contact, has created both the Mesopotamian Basin and the Zagros Mountains. Map by author after Bird, P., 2003, "An Updated Digital Model of Plate Boundaries. *Geochemistry, Geophysics, Geosystems* 4(3): 1027.

Arabian Plate is still moving northwards at 25 millimetres a year towards Asia and, as a result, the Zagros Mountains continue to rise. However, erosion of the mountains balances the uplift, so that the overall height of the land has not changed significantly.

Babylon lay close to the southwestern edge of the Mesopotamian Basin, in which the Euphrates and Tigris Rivers meandered across a 150-kilometre-wide alluvial plain (Figure 3-2). Over millions of years, they deposited vast amounts of sand and mud, effectively burying any older rocks. In this vast plain, the wind has created dunes and, elsewhere, there are shallow saline lakes, but only the tells, the remains of ancient cities, stand out clearly (Plate 6a). This environment may seem

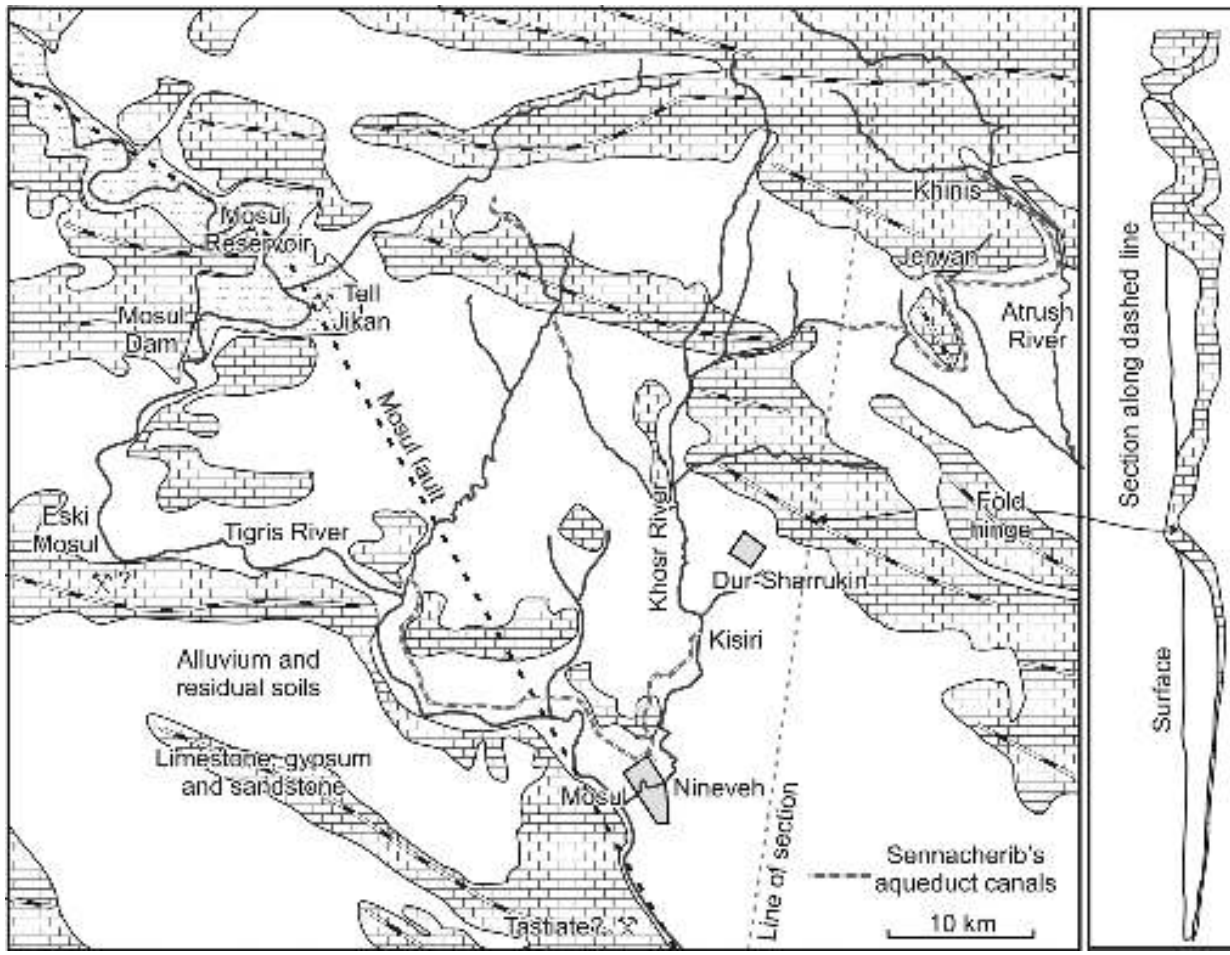


Figure 3-10: The landscape around Nineveh and Mosul is dominated by a series of ridges made of limestone, sandstone, and alabaster (gypsum rock), surrounded by alluvium and residual soils. Horizontal compression has deformed the bedrock into a series of folds that become larger to the east, culminating in the Zagros Mountains. Rock layers resistant to erosion poke up through the hinges of the folds, creating the ridges. Map by author after Ur, J., 2005, "Sennacherib's Northern Assyrian Canals: New Insights from Satellite Imagery and Aerial Photography." *Iraq* 67(1): 317–345.

harsh, but these young alluvial sediments can produce abundant crops if supplied with enough water.

Unlike Babylon, Nineveh stood close to the boundary between the Arabian and Eurasian tectonic plates (Figure 3-9). Here, the direction of movement is oblique to the boundary of the plates, thus creating folding and faulting of the rocks. The folds have produced a distinctive landscape around Nineveh: broadly parallel ridges project up through a plain of river-deposited sediments (alluvium, Figure 3-10). These ridges provided many natural resources: limestone for the walls and

buildings of Nineveh, alabaster for the panels and statues, and water from springs that fed streams and canal aqueducts.

The Mosul fault, the most important in the region, determined the path of the Tigris River near Nineveh (Figure 3-10).[118] This fault may be very old, dating from the initial collision of Arabia and Eurasia sixty million years ago.[119] It moves periodically and produces frequent, but small, earthquakes that cause little damage. The weakness of seismic activity here, despite the large movements of the crustal blocks, indicates that it may be slipping all the time, lubricated by soft minerals such as salt and gypsum. Movements along the fault have kept it open to the circulation of water from the surface to great depths, where it is warmed by the natural heat of the earth and rises to debouch at sulphurous springs near the Tigris 20 kilometres south of Mosul. These warm springs were known for a very long time for their medicinal qualities. Elsewhere along the Mosul fault, there are other warm springs, as well as natural oil and bitumen seeps, which I will discuss later. There have also been vertical movements of the fault, which is why there are high banks along the western side of the Tigris, preventing the river from meandering westward.

In addition to limestone, there is another culturally important rock in this area: alabaster, which is easy to carve and can take detail and so it was used for monumental sculptures and wall slabs. It was probably extracted from many small quarries in the region that have not been identified (Figure 3-10, Figure 3-11). Geologists use this name only for a rock dominated by crystalline gypsum, but archaeologists sometimes extend the meaning to include some types of limestone. There is another source of confusion: locally this rock is called "Mosul marble," but it is not marble in the geological sense, which is metamorphosed limestone.[120,121]

Much alabaster was produced by the evaporation of seawater in shallow coastal lagoons, where the first mineral to crystallize was gypsum ($CaSO_4 \cdot 2H_2O$), not halite (NaCl, common salt) as might be expected. Such deposits are rarely pure and other minerals are also present, such as clay that was washed or blown into the lagoons

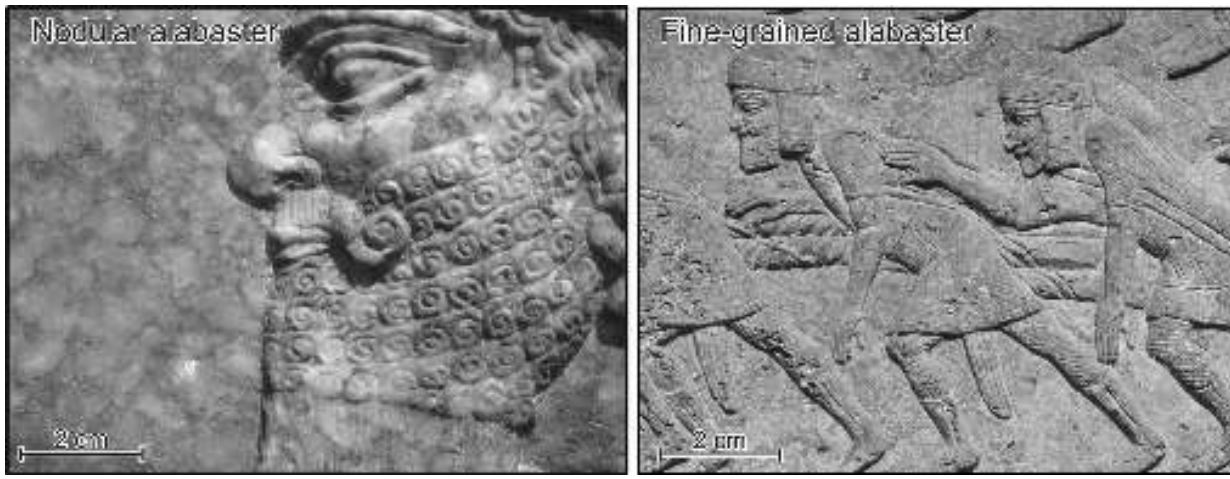


Figure 3-11: This panel is made of nodular alabaster with pale gypsum crystals up to ten millimetres long separated by darker clay and organic material. Some panels were made from a more uniform alabaster with pale gypsum crystals less than two millimetres long. Photos courtesy of the author.

as well as organic matter from bacteria and algae that lived in the water.

The colour and texture of alabaster can be quite variable (Figure 3-11). Nodular alabaster has rounded, pale patches of pure, white gypsum that were formed by recrystallization of small crystals of gypsum from the original mud. Impurities, mostly clay, were pushed aside into the pale-grey matrix. In some places, alabaster also contains small amounts of hydrocarbons, derived from original organic matter, that have been oxidized after exposure to the air to carbon, so that the original pale-grey rock has become deep grey. The more uniform varieties of alabaster used for the wall panels had smaller crystals of gypsum and fewer impurities.

Alabaster, however, has one important weakness as a cultural material: it is easily dissolved by water. Sculptures and panels were originally installed inside buildings to protect them from the weather: in some places, they continued to be protected by building debris after the collapse of the walls. However, archaeologists have not always been aware of this problem and have left material exposed after excavation. Another weakness of alabaster is that it is destroyed by heat: the main mineral, gypsum, contains water and when this is driven out by

fire, the rock turns into a loose powder composed of the anhydrous $CaSO_4$ (anhydrite).

The brackish runoff produced when rain falls on alabaster can accumulate in lakes, where evaporation makes new deposits of alabaster, as is seen in many parts of the Mesopotamian Plain. The mineral can also be dissolved along cracks below the surface producing fissures and caves, a process similar to that which makes a karst landscape in regions with limestone and marble (see Chapter 4). However, alabaster is a much weaker rock than limestone and hence the newly formed cavities collapse easily. Indeed, the modern Mosul Dam is a good example of this as it is continually being undermined by solution of gypsum and could also collapse, inundating Mosul City and Nineveh.

Geology not only determined the mineral resources needed for the development of the cities of Babylon and Nineveh but also the availability of another essential factor: water that was pure enough for agriculture and human consumption.

Water Supply

The climate of Mesopotamia varies enormously between the northern, central, and southern parts. Around Babylon, rainfall is now about 100 millimetres per year, and this may fall in a few short storms from November to April. In this situation, water tends to flow across the ground to feed the rivers rather than sinking in and increasing the amount of groundwater. In this situation, agriculture depends on irrigation. The rainfall near Nineveh is much greater, now about 400 millimetres, mostly falling in the winter, which is sufficient for rain-fed agriculture. Wheat and rye actually originate from this region and were cultivated widely in antiquity. Barley was grown further south, where crop failures were more frequent. Sheep were grazed on more marginal land and would also have consumed cereal waste and failed crops. However, climates are variable, both now and in antiquity, and

long-term changes may have had a strong effect on the history of the region.

A record of rainfall during the last four thousand years was obtained from a stalactite in the hills southeast of Nineveh[122] (see Chapter 1, box 1-3: Getting Information on Ancient Climates). It was found that the climate was significantly wetter from 860 to 780 BCE, which corresponds to a period of rapid expansion of the Assyrian Empire. At that time, much of northeast Mesopotamia would have been suitable for rain-fed cereal farming, and this agricultural wealth could have enabled the territorial ambitions of those in power. The victors of these conflicts then displaced huge populations back to Assyria to work in their cities and fields. This situation could not last forever: the climate became progressively drier over the next hundred years, reducing crop yields as well as the area under cultivation. A major long-term drought started during Sennacherib's reign, which may have been why he constructed a network of irrigation canals that I will write about later. But first, what about the two great perennial rivers of Mesopotamia?

There is no doubt that the Tigris and Euphrates Rivers were important sources of water. Both are rich in tradition and history: in the biblical book of Genesis, contemporary with Nebuchadnezzar II, they are two of the four rivers that flow out of Paradise (from Persian for "walled enclosure"), known also as the Garden of Eden, perhaps indicating a conflation of sacred and royal gardens. These rivers rise in the mountains of central Turkey, where they derive most of their water, before flowing through the dry lands of Mesopotamia, to merge close to the Persian Gulf (Figure 3-2). However, the behaviours of the Euphrates near Babylon and the Tigris near Nineveh were very different.

The Euphrates River near Babylon flows across a wide, flat plain in sinuous loops that slowly snake across the landscape. The riverbed migrates by erosion of the outside edges of the bends—called meanders after the ancient Meander River (now Büyük Menderes) in western Turkey. Such a meandering riverbed can also move abruptly into a new channel by a process called avulsion, typical of river plains with

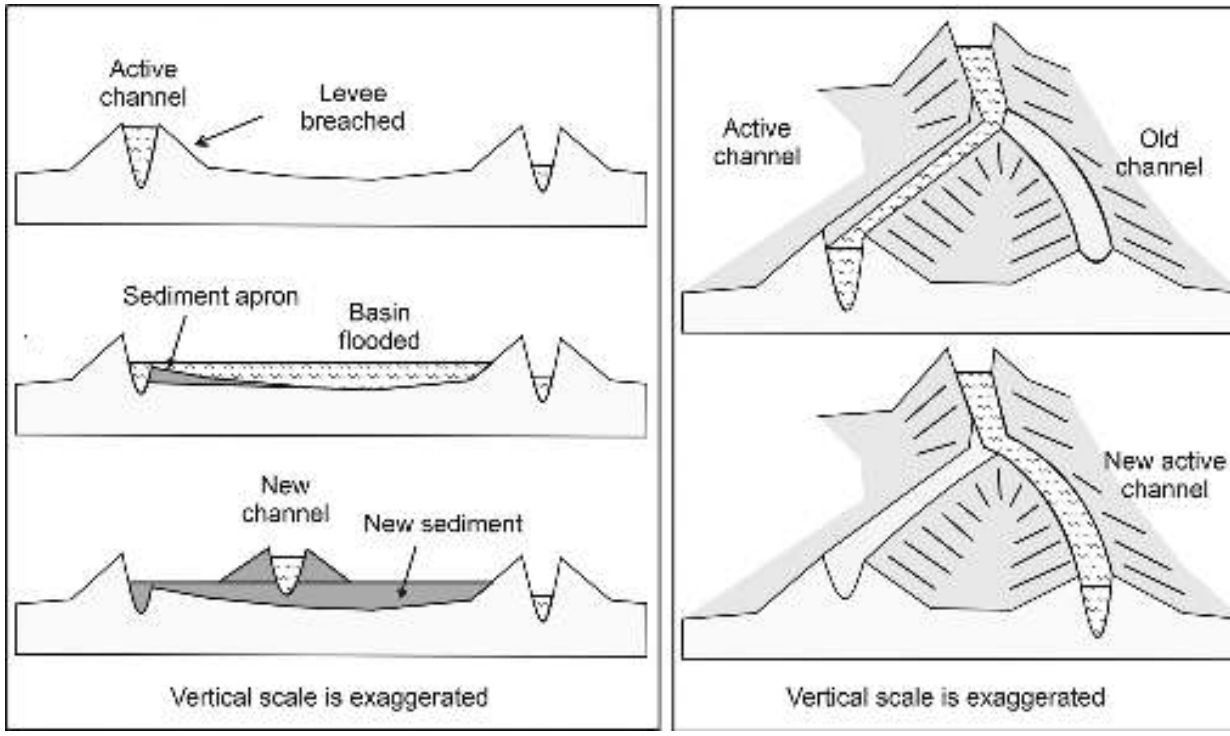


Figure 3-12: Changes in the course of the rivers that flow over the Mesopotamian Plain can occur by avulsion, a rapid process that happens when a levee is breached or the river suddenly reoccupies an older, existing channel. Image by author after Morozova, G.S., 2005, "A Review of Holocene Avulsions of the Tigris and Euphrates Rivers and Possible Effects on the Evolution of Civilizations in Lower Mesopotamia." *Geoarchaeology* 20(4): 401–423.

shallow gradients, as at Babylon.[123] Here, the river deposits sediments close to its banks, where the water moves more slowly, eventually forming levees several metres above the surrounding area. When the levee is breached, naturally or by human intervention, the water floods out onto the adjacent plain to make a swamp or lake (Figure 3-12). Near the break, sediments are deposited as an apron that fans out from the levee. Eventually, the flow of water into the lake will be channelled and a new riverbed will be formed, together with levees. Avulsions can also occur by the reoccupation of older river channels (Figure 3-12). Meandering riverbeds and avulsions have covered the Mesopotamian plain with ancient river channels, most of which are now dry.

The levees and sediment aprons produced by avulsions were good sites for cultivation: they were easy to irrigate, as river water was generally nearby, and well-drained, so were not susceptible to salt

accumulation. Finally, they were less prone to spring flooding, which I will explain later.

Control of avulsions was extremely important in ancient Mesopotamia. They could be prevented by dredging the riverbed and maintaining the levees. Avulsions could also be deliberately induced, for positive or negative reasons: rivers could be diverted to spread water and sediment onto the plain and enlarge areas suitable for cultivation or to starve cities downstream of water and enable conquest, which the Persian emperor Cyrus did at Babylon in 546 BCE.

Unlike the Euphrates, the Tigris in northern Mesopotamia is commonly confined to a narrow valley. Near Nineveh, the river is confined on the west by cliffs, but on the eastern bank, the land rises gently to low hills, restricting, but not eliminating meandering movements of the river (Figure 3-10). The gradient of the riverbed is steeper than at Babylon, so avulsions are less common.

The flow of both the Euphrates and Tigris varies immensely during the year, with a spring flood in April or early May caused by snowmelt and spring rain at their headwaters in the mountains of Turkey. The flood on the Euphrates at Babylon was relatively benign compared with the destructive floods of the Tigris at Nineveh. This is because the Tigris arises from karst springs which respond rapidly to rain or spring snowmelt (Figure 3-13).[124,125] In addition, upstream of Nineveh, steep banks confine the Tigris preventing floodwaters from dissipating by overflow onto the floodplain. As a result, water flow during floods can increase rapidly by a factor of eighty. This was well known in antiquity and may be the origin of the Sumerian name of the river, Idigna, *Swift River*.

Flood myths are common throughout the world, but one of the earliest was recorded in the Epic of Gilgamesh, probably first told in about 1800 BCE. The protagonist was likely a ruler of Uruk, a city downstream from Babylon on the Euphrates, but the story is known to us from cuneiform tablets found in the library of Ashurbanipal at Nineveh and is retold in the Bible as Noah and the Ark (Figure 3-2). These mythical floods can be considered geomyths since they must

Figure 3-13: The expedition of Shalmaneser III in 852 BCE to the cave at one of the sources of the Tigris River in Turkey was illustrated on the bronze gates of the Palace at Balawat in northern Iraq. Drips from the roof formed stalagmites on the floor of the cave. King, L.W., 1915, Bronze reliefs from the gates of Shalmaneser, King of Assyria BC 860–825. British Museum: London.

have been rooted in historical floods of the Mesopotamian rivers, especially the Tigris (see Chapter 1).

Unfortunately, the annual flooding of the Tigris and Euphrates did not benefit agriculture as they did not come when water was needed for planting but rather in the harvest season when they were more of a threat than an asset.[126] The Assyrians at Nineveh got around this problem—and another one caused by a change to a drier climate[122]—by constructing canals. These structures were principally used for transporting water and so should be referred to as aqueducts, even though they were wide enough in places that they could have been used by boats (Figure 3-14).

After Sennacherib came to power, he started an ambitious program of canal building for irrigation around his new capital at Nineveh. This was not the first of such projects. His father and grandfather

had done the same for their capitals, but his program was on a larger scale—an inscription towards the end of his reign lists eighteen canals. He needed to expand the total area of irrigated lands to accommodate all the people that he had conquered and deported to Assyria—some five hundred thousand by his count. It is also possible that reductions in rainfall necessitated irrigation of previously rain-fed fields. It is not always easy to trace the route of the canals now, as recent wars and urban development have modified the landscape. However, we are fortunate to have declassified spy satellite photographs taken in the 1960s, that reveal the ancient canal routes more clearly.[116]

Sennacherib's first project took water from the Khosr River at Kisiri and diverted it into a channel 13 kilometres long (Figure 3-10). This ran to the north of the river and delivered water at a higher level to fields, orchards, and ultimately his new palace and gardens at Nineveh (Figure 3-8). The canal appears to have been somewhat successful, but the amount of water flowing in the Khosr River was not always adequate. He, therefore, embarked on a much larger construction program to augment the flow of the river. He started by clearing out and linking several karstic springs (see Chapter 4) in the limestone ridges north of the city. He then had a long canal constructed to the northwest, whose route is not completely known.

His last project was an ambitious program to tap the Atrush River in the foothills of the Zagros Mountain, 40 kilometres to the northwest. The drainage basin here is small, but this is compensated by higher rainfall than at Nineveh. Sennacherib had a dam of limestone blocks constructed at Khinis to divert the river into a canal 55 kilometres long that added water to the Khosr River. This last canal was an impressive undertaking: part of it ran through a tunnel and elsewhere it crossed another watershed on a stone aqueduct 280 metres long, one of the largest projects of that time (Figure 3-14).[117]

The ancients also used groundwater, water held within soil and bedrock. Some of it reached the surface at natural springs, commonly where an impervious layer of rock guided water to the surface, but mostly it had to be accessed by artificial means. In mountainous

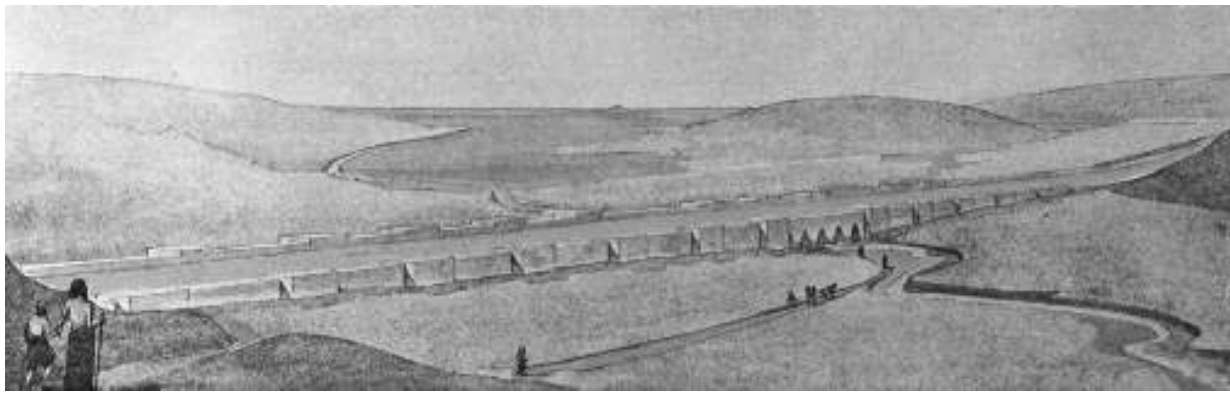


Figure 3-14: Sennacherib built a large stone bridge at Jerwen to enable an aqueduct canal twelve metres wide to cross a small valley. It was repurposed later as a military bridge. Jacobsen, T. and S. Lloyd, 1935, *Sennacherib's Aqueduct at Jerwan*. The University of Chicago Press: Chicago, Ill. 52.

regions, the water table could be reached using gently sloping tunnels called *qanats* that created a kind of artificial spring. It could also be exploited by wells that were dug down from the surface to the water table (see box 3-3: Lugalakia—God of Underground Water).

If groundwater is to be useful for agriculture or human consumption, then it must have a low salt content and be relatively close to the surface, so that it can be easily reached with wells. In Mesopotamia, the water table increases from about 1 metre deep near the Persian Gulf to 30 metres in northeastern Iraq and over 100 metres in the western desert.[127] Near Babylon, water is encountered at a depth of 2 metres, which is almost ideal for agriculture. At Nineveh, the water table is generally much deeper and wells would only have been useful just next to the Tigris River. The quality of the groundwater varies in the other sense: near the coast, the water is brackish and becomes fresher upstream. At Babylon, groundwater is usable, but only just—long-term use of such water for agriculture would lead to accumulation of salts in the soil and reduced fertility. However, this was not a significant problem in antiquity, as the annual floods of the Euphrates spread out over the plains, recharging the soils with fresh water and flushing out salts.

The Tigris and Euphrates did not just transport water; they were also laden with sediments, which were deposited on the floodplain,

Box 3-3 Lugalakia—God of Underground Water

The presence of Lugalakia, the god of underground water, in the Babylonian pantheon shows just how important this resource was in ancient times. We know of this god from a cuneiform tablet that dates from the time of Nebuchadnezzar and proposes that all the gods were just aspects of a supreme being, Marduk, whose temple-ziggurat stood at the centre of Babylon. Each god is listed on a separate line and the second reads "Lugalakia is Marduk of underground water."[98] The other lines include "Adad is Marduk of rain"—Adad had other responsibilities and was also called "the canal inspector of heaven and earth"; "Ninurta is Marduk of the pickaxe," that is labour, and "Nabû is Marduk of accounting," as well as literacy and scribes.

thus providing a continually renewed source of mud, vital for agriculture and construction projects. River muds are composed of tiny grains of clay and other minerals, formed by the chemical breakdown of feldspars in rocks and soils. Clay grains stick to each other and make the mud plastic because of their structure: they are like a deck of wet playing cards in which the water between the cards lubricates them and capillary action keeps them together. Also, the edges of the clay particles have an electric charge that attracts water molecules, so that even when the clay appears to be dry, there is enough water to stick the grains together.

Construction Materials

Mud bricks were the most important building material in Mesopotamian cities. For Babylon, this is understandable as there are no outcrops of stone close by, but this was not the case for Nineveh where limestone was locally available. At Nineveh, mud brick may have been used for traditional reasons, or simply because it was cheaper.

Mud bricks were made from the sediments washed down from Turkey and deposited during the annual floods of the Euphrates and Tigris Rivers. The mud was mixed with straw for strength, moulded, and air dried. They could be made in vast quantities without the need for ovens and fuel. When a mud-brick building collapsed or was demolished, mud from the old bricks was not recycled, possibly because the decayed straw weakened the mixture. Instead, the remains were flattened down to receive the new building, made freshly from river mud and new straw. Over thousands of years, the base level of cities rose above the river plains to form substantial mounds called tells. As the tells increased in height, the city became better protected from floods and more easily defensible, thus encouraging more occupation and construction.

Mud bricks have an obvious drawback: they are easily washed away or damaged during storms. But there is another problem: groundwater is drawn up into the bricks at the base of the walls by capillary action and evaporates. Salts are concentrated and finally crystallize between the mineral grains, causing the mud to flake, weakening the base of the walls. This was very important at Babylon, where the groundwater was quite brackish. It was discovered early on that mud could be transformed into a hard, impermeable material by baking, eliminating many of these weaknesses.

Heat changes water-bearing clay minerals, with their slippery playing-card structure, into larger interlocking crystals of minerals containing less water, which make a stronger material that is water resistant. The overall transformation is similar to metamorphism, the natural process that makes marble and schist (see Chapter 6), but the minerals that are developed are not always the same, as the firing of bricks is millions of times faster than metamorphism and happens at a much lower pressure. The monumental structures built by Nebuchadnezzar were mostly constructed of baked brick. Indeed, so many bricks were made that, for long after its fall, Babylon was a veritable "brick mine" for the construction of Baghdad and other cities.

A vast amount of fuel must have been needed to bake the bricks for Nebuchadnezzar's city. There are no forests near Babylon now, nor were there in antiquity. Shrubs and brush could have provided some fuel, but it seems unlikely to have been enough. There was, however, another fuel available nearby: bitumen from the springs at Hît, which I will describe later. This bitumen had a high sulphur content and the firing process must have produced huge quantities of smelly sulphurous gasses. But I should mention that there is no documentary evidence of bitumen having been used as fuel for brick ovens.

The wide walls of Babylon were one of the Wonders on Philo's list. The walls themselves were made of mud brick, but the gates were faced with baked bricks glazed in bright colours.[128] The Ishtar Gate and adjacent Processional Way were the largest and most impressive part of the walls and have been partly reconstructed in all their glory (Plate 5a; Plate 5b). The dominant colour was blue, with animals depicted in yellow and white, with green accents. There were lions and aurochs (wild cattle), which were part of the local fauna at that time, as well as dragons that were not.

The glazes used on the bricks were chemically similar to glass (see Chapter 8), and the same colouring agents were used in both materials. The blue glaze was made using copper and cobalt.[129] As is the case for many materials, the discovery of *cobalt blue* was probably made accidentally by a potter. Primary cobalt minerals are rather dull (the ore cobaltite, CoAsS, is dark grey) but commonly alter to a striking pink mineral called erythrite or "cobalt bloom" ($Co_3[AsO_4]_2 \cdot 8H_2O$). A potter may have tried to use this mineral to produce a pink glaze and was surprised to see that it gave a deep blue colour. Copper and cobalt may have come down the Euphrates from deposits near the Black Sea coast of Turkey, as suggested by the ancient Sumerian name of the river, Buranuna, possibly *Copper River*.[129,130] A rich deposit of cobalt in central Iran at Qamsur (near Kāshān) may have been used, although mining was most intense during the mediaeval period when it supplied pigment for the production of Islamic and Chinese blue glazes.[131]

The green, yellow, and white glazes were coloured respectively with copper, lead, or calcium, together with antimony as an opacifier to hide the underlying substrate.[129] Antimony (Sb) may seem like a rare and exotic ingredient, but it was commonly used in black eye makeup called *kohl*, which was made of powdered stibnite (Sb_2S_3), or galena (PbS), mixed with fat. Both minerals occur as easily recognized metallic-grey crystals and are commonly found in limestone. The Babylonians probably obtained them from deposits in the Taurus Mountains of Turkey.[129]

Although baked and unbaked bricks were the dominant construction material of Babylon, limestone was used for special purposes but must have been expensive, as it was imported from the mountains far to the east. So it is not surprising that the impressive glazed brick gate and walls of the Processional Way were complemented by a limestone pavement, as were a few rooms in the Palace. At Nineveh, however, limestone was readily available in the surrounding hills and was used to build the walls and parts of the palace.

In many ancient cities, stones and bricks were set in lime mortar—made by heating limestone or marble to high temperatures (see box 4-4: Stucco and Frescoes)—but this was difficult at Babylon as both limestone and fuel were in short supply. So, what did the ancient Babylonians use instead? Bitumen, the solid hydrocarbon, also known as tar or asphalt.

Bitumen and Other Hydrocarbons

The bitumen resources of Mesopotamia were well known in antiquity. Herodotus mentions that "The bitumen used in the work [construction of the walls] was brought to Babylon from the Is [Id], a small stream which flows into the Euphrates at the point where the city of the same name stands, eight days' journey from Babylon [~200km]. Lumps of bitumen are found in great abundance in this stream."[53] Diodorus Siculus, who gave us his description of the Hanging Gardens, wrote:

"While many incredible miracles occur in the Babylonian country, there is none such as the great quantity of bitumen found there. It is not only sufficient for so many and such large buildings but the yield, as with a rich well, remains inexhaustible."[132]

Bitumen is the heavy, solid residue that develops near the surface from liquid petroleum ("crude oil"), after the lighter, more volatile components evaporate. It had many uses and was an important trade commodity in ancient Mesopotamia from the 4th millennium BCE onwards.[133,134] It was used as a mortar to cement baked bricks in city walls and other buildings; to set the alabaster wall panels that decorated the walls of the palaces; to prevent water from rising into mud-brick walls; to pave roads, as it is used now; in shipbuilding; and to waterproof other structures. It was also used in medicine and agriculture as an insecticide on vines and fruit trees. It was used extensively in the construction of gardens to waterproof walls and channels. It could be mixed with clay to make *bitumen mastic*, a hard plastic-like material that was carved into statues. Bitumen from the Dead Sea was used in Egypt for mummification after about 1000 BCE, to replace tree resins (see Chapter 2).

Petroleum originates deep in the earth from ancient plant matter trapped in mud and sand deposited in rivers, lakes and the sea. Accumulation of more material forces the sediments down into the earth, where increases in temperature and pressure transform the loose sediments into rock, and the entrapped organic material into petroleum.

The Middle East is well known for its huge reserves of petroleum. Such an important resource requires an unusual series of events that first generate the hydrocarbons, then let it migrate to traps where it accumulates, and is preserved from destruction or loss.[135] It all began on the north coast of the African-Arabian continent, where the land was close to sea level for almost five hundred million years. During the Cretaceous period (140–60 million years ago), the climate was generally warm and wet, so plants grew well and sediments containing much organic matter were deposited in the sea and shallow,

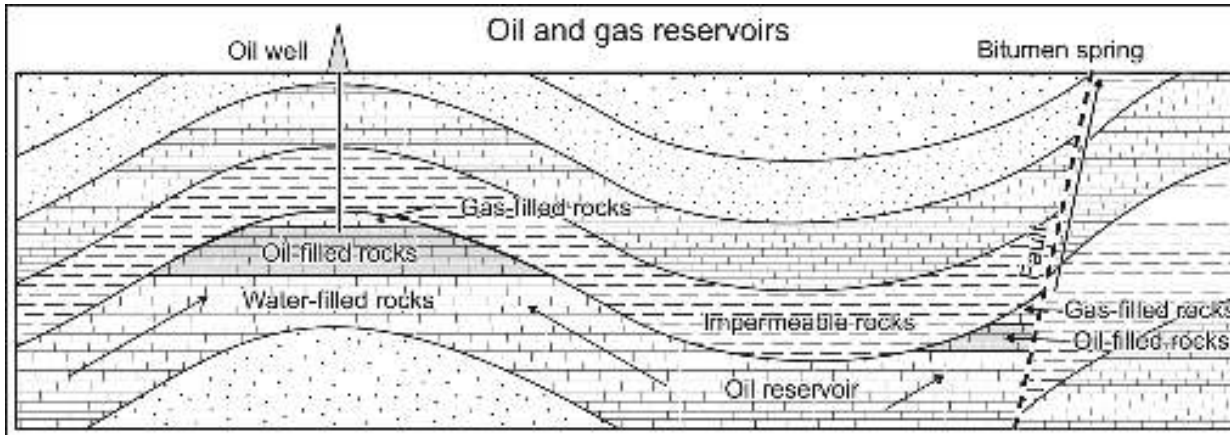


Figure 3-15: Petroleum (oil) is lighter than rock or water and will move towards the surface unless stopped by impermeable rocks such as shale and alabaster. In some places, there are gas-filled rocks above the petroleum-rich layer. The hydrocarbons are trapped in porous reservoir rocks, such as limestone, which can be tapped by drilling. If petroleum leaks up a fault towards the surface, then its volatile components may be lost leaving behind bitumen, which can appear at springs, along with water and natural gas. Image by the author.

ephemeral lakes. Thick piles of sediments accumulated and were transformed at depth into oil-bearing limestone, shale, and alabaster. When the Arabian subcontinent collided with the Eurasian continent, it created not only a mountain range but also gentle folding and faulting of the rocks in the Mesopotamian basin. These structures trapped the petroleum under layers of impermeable rock (Figure 3-15). Finally, the geological stability of the region meant that the rocks were not subjected to high temperatures that would have destroyed the hydrocarbons.

There were many bitumen springs in Mesopotamia, but the most important were at Ain Hît (ancient *Is* or *Id*), near the Euphrates about 200 kilometres northwest of Babylon.[127,137,138] Indeed, the Akkadian word for bitumen, *iddu*, came from the ancient name of that town.[139] The bedrock here is porous limestone and the bitumen rises up a series of north-south faults from deeper source rocks (Figure 3-15). The springs yield a mixture of water, bitumen, and natural gas (see box 3-4: Natural Gas Fires), including the smelly, poisonous gas hydrogen sulphide (Figure 3-16).[136] Lumps of bitumen rise to the surface of the springs and are washed downstream by storms to accumulate in the

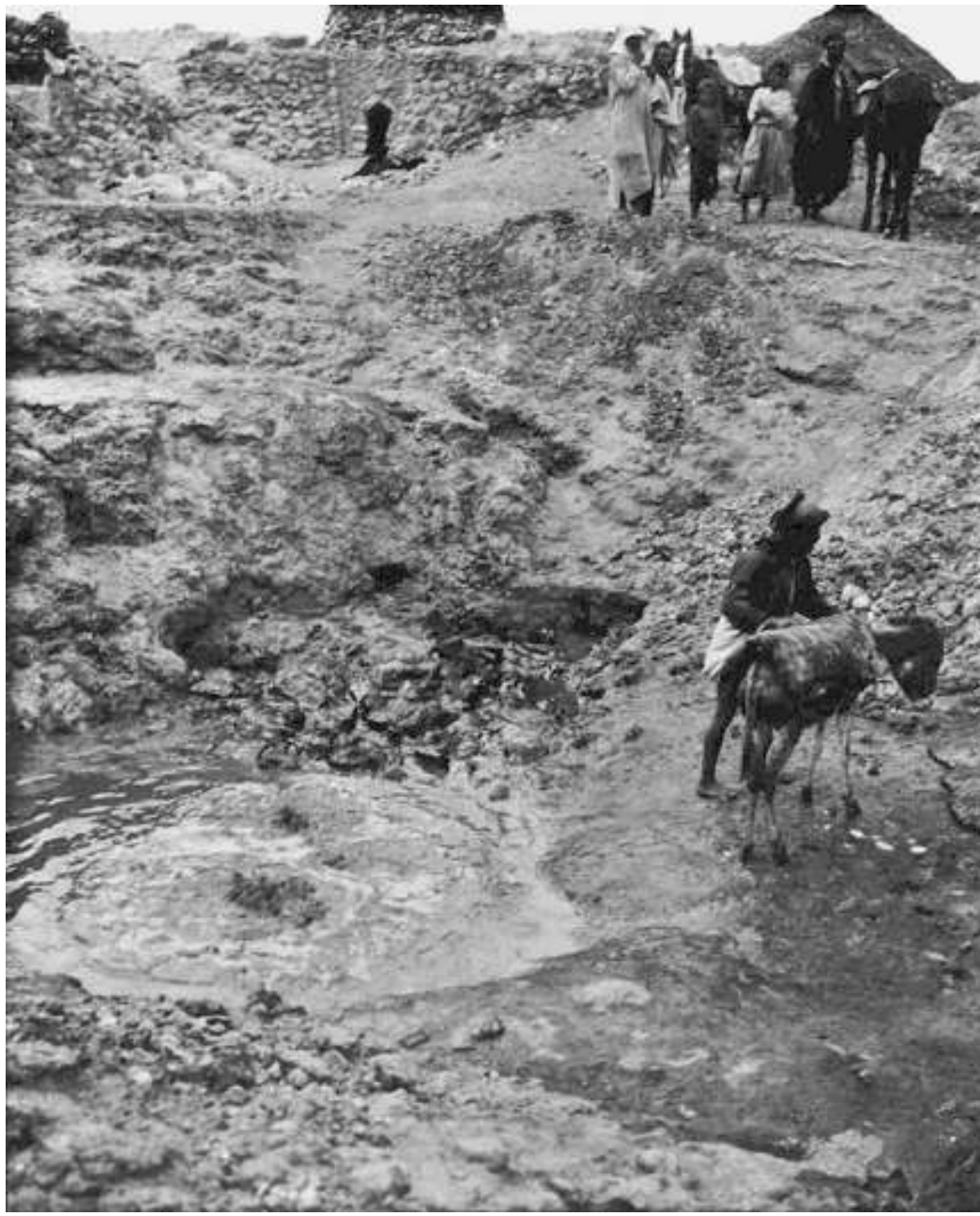


Figure 3-16: Water, bitumen, and natural gas rise to the surface together to fill small pools and streams at Ain Hît. Gertrude Bell visited the springs in 1909 and was not impressed: "We explored the village of Hît before nightfall and a more malodorous little dirty spot I hope I may never see." The local people extracted sulphurous bitumen by heating, probably in the same way as in ancient Babylon. Bell, G.L., 1911, *Amurath to Amurath*. William Heinemann: London.

Box 3-4 Natural Gas Fires

Natural gas leaks out at many places in Mesopotamia and can be ignited naturally by lightning strikes (Plate 7b). Gas fires are difficult to put out as they burn not only at the surface but also underground. The *Eternal fires* of Baba Gurgur, near Kirkuk, were described by Herodotus in the 5th century BCE and are still burning today.[53] Some people believe that the *fiery furnace* of the biblical Book of Daniel, into which Nebuchadnezzar threw three Jews for refusing to worship his golden idol, was such a gas fire. The dominant component of natural gas is methane (CH_4), accompanied by heavier hydrocarbon and sulphurous gasses. Natural gas can be formed from petroleum by burial, in which the natural heat of the earth breaks apart large hydrocarbon molecules into simpler compounds, or as a waste product of bacteria that feed on oil or coal.

stream sediments. In ancient times, lumps of bitumen were collected and processed by heating, liberating yet more sulphurous gasses. The Dead Sea was another ancient source of bitumen, used for mummification in Egypt, especially during Ptolemaic times (see box 3-5: Dead Sea Bitumen and the Nabateans).

The Demise of Nineveh and Babylon

The Assyrian Empire declined rapidly from its zenith under Sennacherib in 670 BCE to its collapse and final defeat by the Babylonians and Medes in 612–609 BCE. Historians have proposed many explanations, but the underlying cause may have been many decades of drought that reduced agricultural production and weakened the state.[122] At Nineveh, the invaders burned the palace of Sennacherib, severely damaging many of the alabaster wall panels and sculptures. Any gardens existent at that time would have vanished after

Box 3-5 Dead Sea Bitumen and the Nabateans

Bitumen is found as huge blobs, weighing up to 100 tons, which float on the dense waters of the Dead Sea. The blobs formed on the lake floor by seepage of petroleum along faults, where it accumulated until it rose to the surface—a similar process occurs worldwide and about half of all marine petroleum pollution may have such a natural source.[146] Ancient writers talked of how the appearance of the bitumen was preceded by the release of a gas that tarnished metals, which was probably hydrogen sulphide ("Rotten-egg gas," H_2S). The blobs still surface occasionally today but are not accompanied by gas, no doubt much to the relief of local people.

Trade in Dead Sea bitumen was controlled by the Nabateans, who are best known for their capital city of Petra. They would collect the bitumen and transport it south, up the gently sloping valley towards Petra, and then westward across the desert to the Nile. The earliest mention of the trade was in 312 BCE when Syria tried to take control—this was the first known war for hydrocarbon resources. Subsequently, the Roman general Marcus Antonius (Mark Anthony) gave Cleopatra, his lover and the Queen of Egypt, exclusive rights to the bitumen, but she was never able to wrest the trade from the Nabateans. The fine architecture of the city of Petra suggests that this must have been a very profitable business.[147-149]

the loss of their imperial patron. Soon after, the site was abandoned and lost, as Lucian put it in the 2nd century CE: "Well, as for Nineveh, skipper, it was wiped out long ago. There is not a trace of it left, and one can't even guess where it was."

After the defeat of the Assyrians, Babylon became the greatest city in the region, as attested by the wealth of Nebuchadnezzar's city. It could sustain its population as agriculture there was based on irrigation and as a result, was less affected by regional droughts.[122] However, this situation did not continue for long and in 546 BCE Babylon was conquered by the Persians under Cyrus the Great. He had realized

that the walls were almost impregnable, but saw that the weakness of the city lay in the river. He had probably seen the effects of natural avulsions and decided to make an artificial one—he destroyed the banks of the Euphrates a few kilometres upstream, diverting its waters into the floodplain. The soldiers then walked into the city along the former riverbed.

Babylon makes a brief reappearance in history in 323 BCE when Alexander the Great unexpectedly died there. It was said to have happened in the garden of Nebuchadnezzar's Palace but it would seem very unlikely that the wondrous garden, if it ever existed here, had been maintained for more than two hundred years since the conquest by the Persians. However, it is entirely possible that another garden was existent at this time.[103]

The city was largely abandoned by the 5th century CE: no doubt political considerations were important, but another factor may have been the loss of agricultural fertility due to the accumulation of salts in the surrounding lands as a result of irrigation and evaporation over the centuries.[126]

Excavation of Kuyunjik Tell near Mosul started in 1842 and the site was soon identified as ancient Nineveh[111] (Figure 3-17). The excavators found vast amounts of sculpture and cuneiform documents, and most were sent to the British Museum (Plate 7a).

What was left in place has not fared well. Rain damaged the newly exposed alabaster panels and sculpture. The site was despoiled during the Iraq civil war, then looting and squatting completed the destruction of any remains close to the surface. ISIS took Mosul in 2014 and destroyed museums, as well as ancient and Islamic monuments.[140] However, in their destruction of the Nebi Yunas (Jonah) mosque they found, and partly looted, a previously unknown Assyrian palace buried deep within the tell.[141]

The location of Babylon was never completely lost, but there was little interest in the site. The remains of the mud-brick walls still poked up through the alluvial deposits of the river, showing the vast size of the ancient city, and fired bricks were "mined" to build Baghdad.

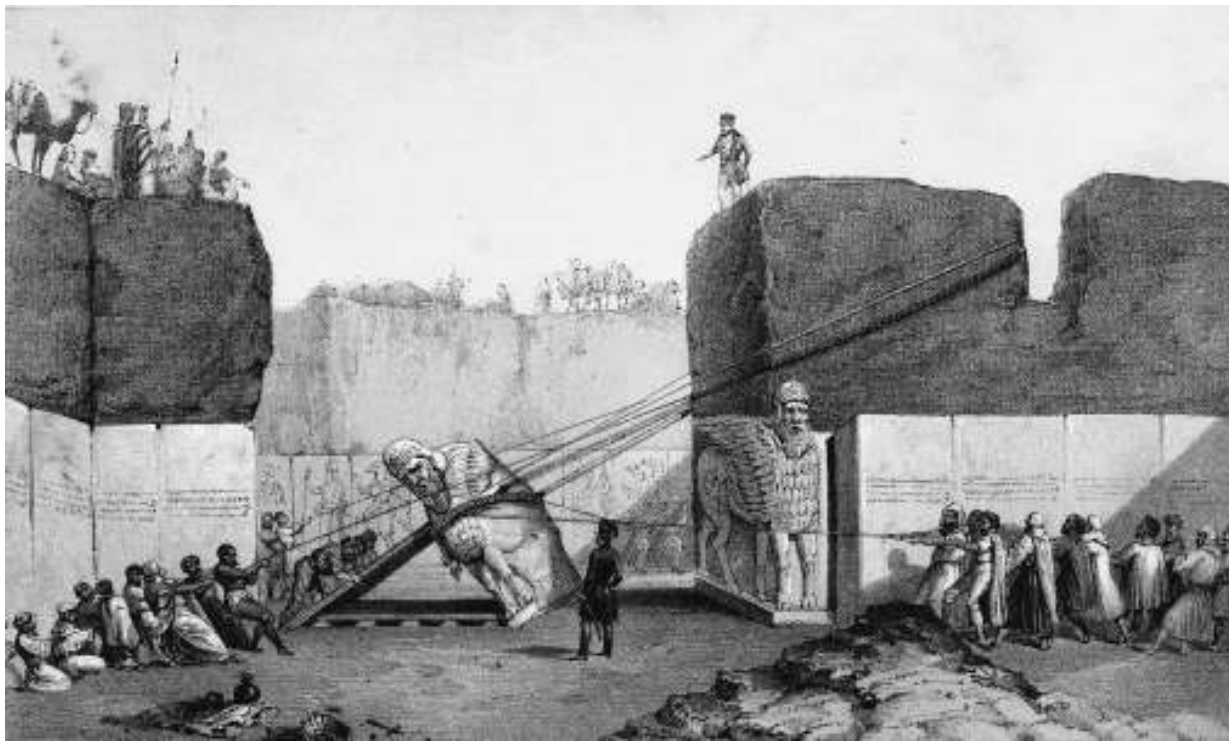


Figure 3-17: Austen Layard (centre top) excavated the North Palace of Ashurbanipal at Nineveh in 1845–1847. The alabaster slabs and sculptures that lined the walls of the palace had been buried in mud derived from mud-brick walls preserving them from erosion by rainwater. The palace of Sennacherib was decorated similarly and was buried somewhat deeper, necessitating excavation by tunnelling. Layard, A.H., 1849, *Nineveh and Its Remains, with an Account of a Visit to the Chalaean Christians of Kurdistan, and the Yezidis, or Devil-Worshippers and an Enquiry into the Manners and Arts of the Ancient Assyrians*. John Murray: London.

However, the *Babil Tell* was just another ancient artificial mound, so common in Mesopotamia.

Archaeological excavations by the Germans from 1899 to 1917 left little at the site to mark its former glory—anything of interest was sent to Berlin and elsewhere.[142] In 1983, Saddam Hussein reconstructed parts of the ancient palace: new bricks were inscribed with his name in cuneiform, like those of the ancient rulers of Babylon, as he considered himself a reincarnation of Nebuchadnezzar II. He also built a mound and palace partly over the western outworks, one of the possible locations of the gardens. In 2003, American invasion forces established a military base near the ancient remains, further damaging the site.[98]

4

The Statue of Zeus at Olympia

The Sanctuary and Statue

> We marvel at the rest of the Seven Wonders but this one we worship.
>
> Philo of Byzantium

Zeus was the father of all—gods and humans alike—and his sanctuary of Olympia in western Greece had to reflect this status. To please him so that he would come down from Mount Olympus to visit his temple during the Olympic Games, an albeit rather modest building was filled to the rafters with his likeness in the form of a spectacular statue (Figure 4-1).[150] It was huge and made of ivory, gold, glass, and other precious materials. It was this statue, not the temple or the sanctuary, that was the Wonder of the World—and perhaps of the heavens!

The site of Olympia has a long history starting with the construction of a ritual tumulus about 4,500 years ago, that was still visible when the sanctuary was established around 1000 BCE, by which time it appears to have been associated with the mythical hero Pelops, after which the whole peninsula was named.[151] Many cult figures of wild cattle and horses have been found in ashes from an early altar, suggesting that Olympia may have been a hunting reserve for aristocrats, dedicated to Artemis, the goddess of the hunt.[152] As wild animals were extirpated, hunting rituals may have been transformed into athletic events, such as

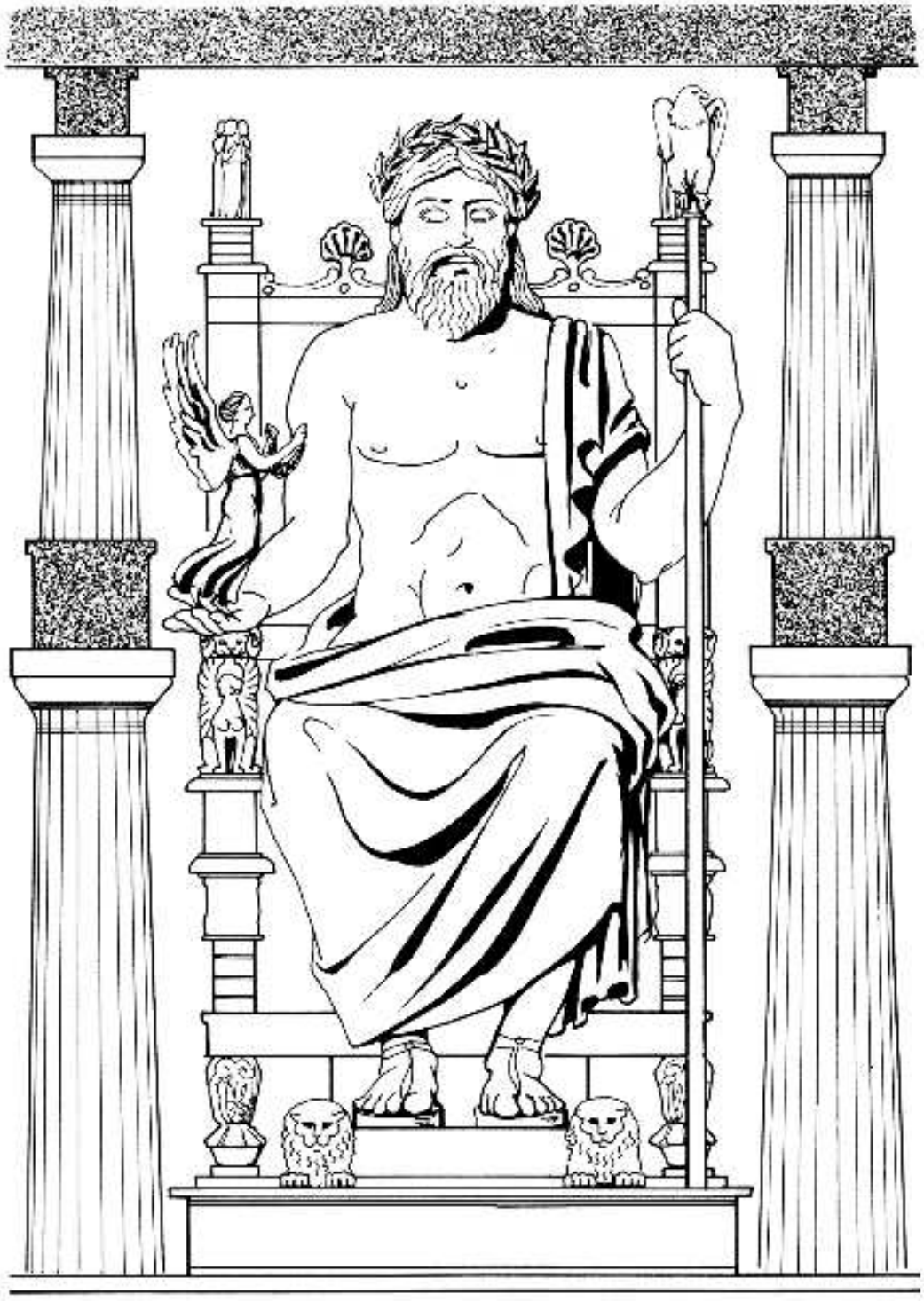


Figure 4-1: The statue of Zeus at Olympia was made of ivory and gold, set on a throne of ebony and other precious materials. A winged figure of the goddess Nike made of glass or gold rested in his right hand and his left held a sceptre crowned with an eagle. The statue stood thirteen metres tall and was housed in a temple that was not much higher. Swaddling, J., 1980, *The Ancient Olympic Games*. British Museum Publications: London.

running, and the dedication transferred from Artemis to Zeus. However, this idea has not been preserved in the founding myths of the games.

The ancients believed that Olympic Games, more accurately translated as Olympic Contests, were founded in 776 BCE, by the Greek hero Heracles (the Roman Hercules). One legend recounts that King Augeas of Elis ordered Heracles to clean the royal stables and promised him a tenth of the cattle if he could do it in one day. Heracles found an innovative solution and diverted the Alpheios and Pineios Rivers through the stables but the king refused to honour the bargain (see box 4-1: Cleaning King Augeas's Stables). Heracles killed him and subsequently commemorated the event by instituting the games in honour of his father Zeus. There were other founding myths as well, none of which seemed convincing to Strabo in the 1st century BCE and we cannot do any better now.[150,153] The games were held regularly for 1,200 years until 393 CE when the Christian Emperor Theodosius I closed the sanctuary. Olympia was named after the home of the gods, Mount Olympus, 280 kilometres to the northeast.

The sanctuary's focus eventually became the great statue of Zeus, which was designed by the sculptor Pheidias and completed in about 430 BCE (Figure 4-1).[150,154] He had already constructed a large statue of Athena for the Parthenon in Athens (Plate 10a) but had left the city in disgrace after accusations of corruption. He may have regarded the new commission as redemption for his previous actions. Nothing survives of the statue of Zeus, but we have a good idea of its likeness from literary sources, coins, and archaeological materials.

The best description that we have is by Pausanias, a Greek religious traveller writing in the 2nd century CE, who described the statue as it was some six hundred years after it was completed. "The god sits on a throne, and he is made of gold and ivory. On his head lies a garland, which is a copy of olive shoots. In his right hand, he carries a Victory [Nike], which, like the statue, is of ivory and gold; she wears a ribbon and, on her head, a garland. In the left hand of the god is a sceptre, ornamented with every kind of metal, and the bird sitting on the sceptre is the eagle. The sandals also of the god are of gold, as is likewise his

Box 4-1 Cleaning King Augeas's Stables

Marble panel from the Temple of Zeus at Olympia showing Heracles shovelling dung under the direction of Athena. Adler, F., E. Curtius, and G. Treu, 1897, Olympia: die Ergebnisse der von dem Deutschen Reich veranstalteten Ausgrabung im Auftrage des Königlich Preußischen Ministers der geistlichen Unterrichts- und Medicinal-Angelegenheiten. Asher: Berlin.

The fifth labour of Heracles, cleaning of the stables of King Augeas of Elis, was rather different from his other challenges: it did not involve killing or capturing unusual animals and was for payment.[159] Although ancient images commonly depict Heracles shovelling the dung in a rather mundane way, a rather more interesting legend has it that he achieved this feat by diverting the Alpheios and Pineios Rivers through the stables.

The mention of these rivers suggests that this story is a geomyth. To start with, both rivers are associated with Olympia: the Alpheios River was adjacent to the sanctuary and the Pineios River ran through the city of Elis, the state that controlled Olympia for much of its history. I've already talked about catastrophic flooding of the Alpheios River, but what of the Pineios? Near Elis, the river runs in a valley formed by erosion along an east-west fault. We know that this fault must have been active recently as the steep cliffs produced by fault movements (fault scarps) are still preserved in the soft sediments of the valley.[194] Movements of the fault during earthquakes may have also caused landslides that dammed the river. Collapse of these temporary dams and subsequent drainage of the impounded water could have caused significant floods at Elis.

robe. On the robe are embroidered figures of animals and the flowers of the lily. The throne is adorned with gold and with jewels, to say nothing of ebony and ivory. Upon it are painted figures and wrought images." . . . "I know that the height and breadth of the Olympic Zeus have been measured and recorded; but I shall not praise those who made the measurements, for even their records fall far short of the impression made by a sight of the image. Nay, the god himself, according to legend, bore witness to the artistic skill of Pheidias. For when the image was finished, Pheidias asked the god to show by a sign whether the work was to his liking. Immediately, runs the legend, a thunderbolt fell on that part of the floor where down to the present day a bronze jar stands to cover the place." Such a sign from the gods is open to interpretation and was not necessarily positive! Other authors were not so enthusiastic about the statue (see box 4-2: Contrasting Opinions).

The only actual images of the statue we have are on coins (Figure 4-2), and these broadly resemble the ancient descriptions.[155] Images of famous statues and other sights were frequently reproduced on coins in antiquity, no doubt partly to encourage tourism, which was a profitable venture then as now.[2, 156] The coins were, in essence then, advertisements and made handsome souvenirs.[157]

Although no traces of the statue have been located, excavators found ancient materials and tools in an adjacent building. The creation of

Box 4-2 Contrasting Opinions

The 2nd century CE satirical writer Lucian of Samosata gave a different perspective on the statue in his work "On Sacrifice": "In spite of all, those who enter the temple and think that what they behold is not now ivory from India nor gold mined in Thrace, but the very son of Kronos and Rhea, transported to earth by Pheidias and bidden to be the overlord of deserted Pisa, thinking himself lucky if he gets a sacrifice once in four long years as an incident to the Olympic Games." [Text and translation: Harmon, LCL 1921]

There is also another memorable quotation from Lucian in "The Rooster." The eponymous narrator speaks of his time as a human king: "I pitied myself for being no better than the great colossi that Pheidias or Myron or Praxiteles made, each of which is outward a beautiful Poseidon or a Zeus, made of ivory and gold, with a thunderbolt or a flash of lightning or a trident in his right hand; but if you stoop and look down inside, you will see a tangle of bars and struts and dowels driven right through, and beams and wedges and pitch and clay, and a quantity of such ugly stuff housing within, not to mention legions of mice and rats that sometimes conduct their civic business there" [Text: Harmon, LCL 1915 Translation: adapted from Harmon]

Strabo (64 BCE–24 CE) was not completely satisfied by the statue either: "But the greatest of these was the image of Zeus made by Pheidias of Athens . . . it was made of ivory, and it was so big that, although the temple was very large, the artist is thought to have missed the proper symmetry, for he showed Zeus seated but almost touching the roof with his head, thus making the impression that if Zeus arose and stood erect he would unroof the temple" [Strabo, Geography VIII.3.30].

the statue was such an important project that a special workshop was built for Pheidias, with the same dimensions and orientation as the room in the temple where the statue was to be erected (Figure 4-4). Pausanias mentions the workshop, and its identity was confirmed by

Figure 4-2: Zeus figured on the reserve side (tails) of these two coins issued by Elis (ΗΛΕΙ), the state that controlled Olympia at that time, during the reign of the Roman Emperor Hadrian (117–138 CE), possibly to commemorate one of his visits to Greece. Boetticher, A., 1886, *Olympia, das Fest und seine Stätte*. Verlag von Julius Springer, Berlin.

fragments of ivory, bone, quartz, obsidian, ebony, amber, lead, bronze, and glass; and artefacts such as clay moulds and tools—there was even a cup with "I belong to Pheidias" inscribed neatly on its base.

The iconography of the statue is clear, as the games were in honour of Zeus and were regarded as a way of worshipping him. He is relaxed, enjoying the games from his comfortable throne. Athletic success came from Zeus, symbolized by Nike, the goddess of victory, in his right hand. The god also punished cheaters with the sceptre that he held in his left hand.

There are no descriptions as to how the statue was made but we can assume that it followed the method already developed for large statues, which would subsequently be used for the Colossus of Rhodes.[154] The first step was the construction of a strong wooden framework, here including both the throne and the core of the statue, either in Pheidias's workshop, or in the temple itself. Next, the spaces between the framework were completed with smaller pieces of wood and the whole covered with a coating of plaster, effectively producing a full-sized, but undecorated version of the statue. The parts of the

statue that were to be rendered in gold were covered with beeswax to a thickness of several millimetres. The wax was carefully removed and prepared for casting by impressing decorations into the surface and adding rods to make channels for pouring the metal. This model was covered in clay that was heated to remove the valuable wax and then fired at high temperatures to make a ceramic mould. The final stage was to melt gold in a furnace and pour it into the mould. After the mould had cooled, it was broken to reveal the casting, which was then finished by trimming, hammering, and polishing. The casting would have then been fixed to the framework with pins. Ivory was shaped and fixed to the framework (see later), as were other materials like ebony. In the completed statue, the original wood and plaster model was completely covered by precious materials, although its internal structure could still be seen from the back (see box 4-2: Contrasting Opinions).

The statue was erected inside a temple completed about twenty years earlier in 455 BCE (Figure 4-3).[158] The common story is that Pisa, a city beside the sanctuary, was sacked by the army of Elis and the victors used the plunder to finance the new temple. However, we don't know if Pisa even existed at this time and the cost of the temple, estimated at 300–400 talents of silver (~5–8 million dollars), far exceeds the booty from any Greek internal conflict.[159] However, in 479 BCE, a combined army of Greeks defeated the forces of the Persian Empire at Plataea near Corinth and the proceeds of this battle would have been ample for the construction of the temple and perhaps even the statue. Such a project would also have created a fine Panhellenic monument, reminding Greeks of their heritage every four years.

The temple was made of a local shelly limestone faced with stucco, with minor sculptures and roof tiles of high-quality white marble (see box 4-4: Stucco and Frescoes). Later, the statue of Zeus was installed inside the temple on a one-metre-high plinth of dark grey limestone, behind a stone basin filled with olive oil or possibly water. The idea was that the liquids would reflect light onto the statue and their vapours would prevent the ivory from cracking.

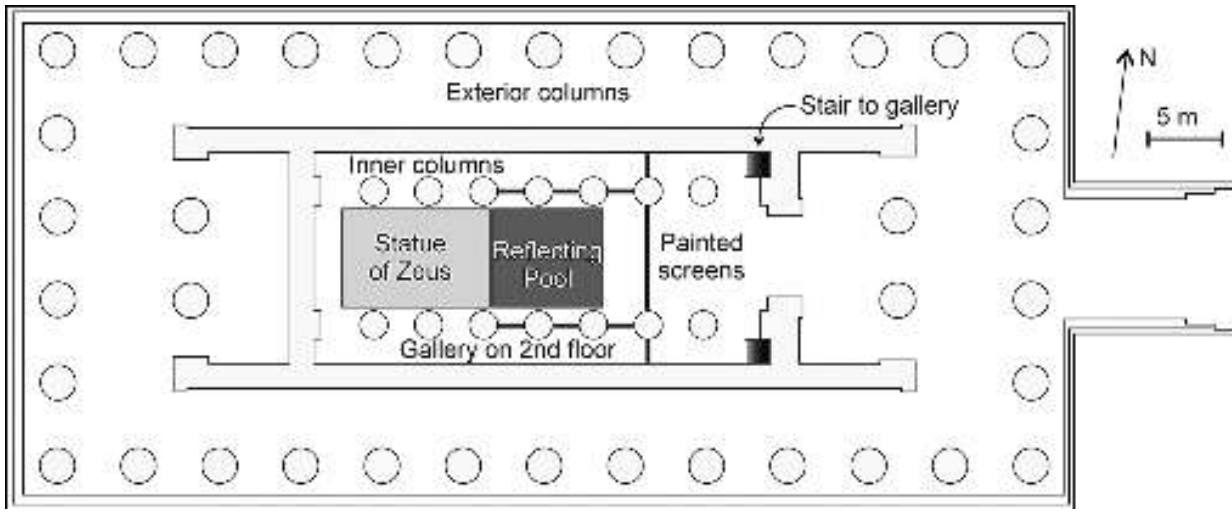


Figure 4-3: The statue of Zeus stood on a pedestal within the temple's inner colonnade. There was a shallow pool for oil or water in front of the statue and access to the whole ensemble was controlled by nine painted screens. There were viewing galleries at a mid-level supported on the inner columns. Image by author after Adler, F., E. Curtius, and G. Treu, 1897, Olympia: die Ergebnisse der von dem Deutschen Reich veranstalteten Ausgrabung im Auftrage des Königlich Preußischen Ministers der geistlichen Unterrichts- und Medicinal-Angelegenheiten. Asher: Berlin.

Access to the statue and pool was controlled by nine painted stone screens (Figure 4-3). We don't really know much about them but they clearly impressed Pausanias in the 2nd century CE who gave a long description of their images. As so little painting has survived from this period, it is easy to forget that at that time it was considered to be equal to sculpture and this is exemplified by wall paintings from Akrotiri on Thera, one thousand years before the statue and Pompeii, five hundred years after. The images at Olympia likely resembled those on pottery, sculpture, and buildings from the period, with a palette of red, blue, yellow, white, and black. The first two colours were also used on the Mausoleum: red was natural ochre and blue was an artificial material called Egyptian blue (see Chapter 5). Yellow was probably limonite (hydrated iron oxide), white was probably powdered limestone or marble, and black would have been charcoal or manganese oxide. The paintings may have been "true" frescoes, painted on damp lime plaster applied to a masonry wall (see box 4-4: Stucco and Frescoes).

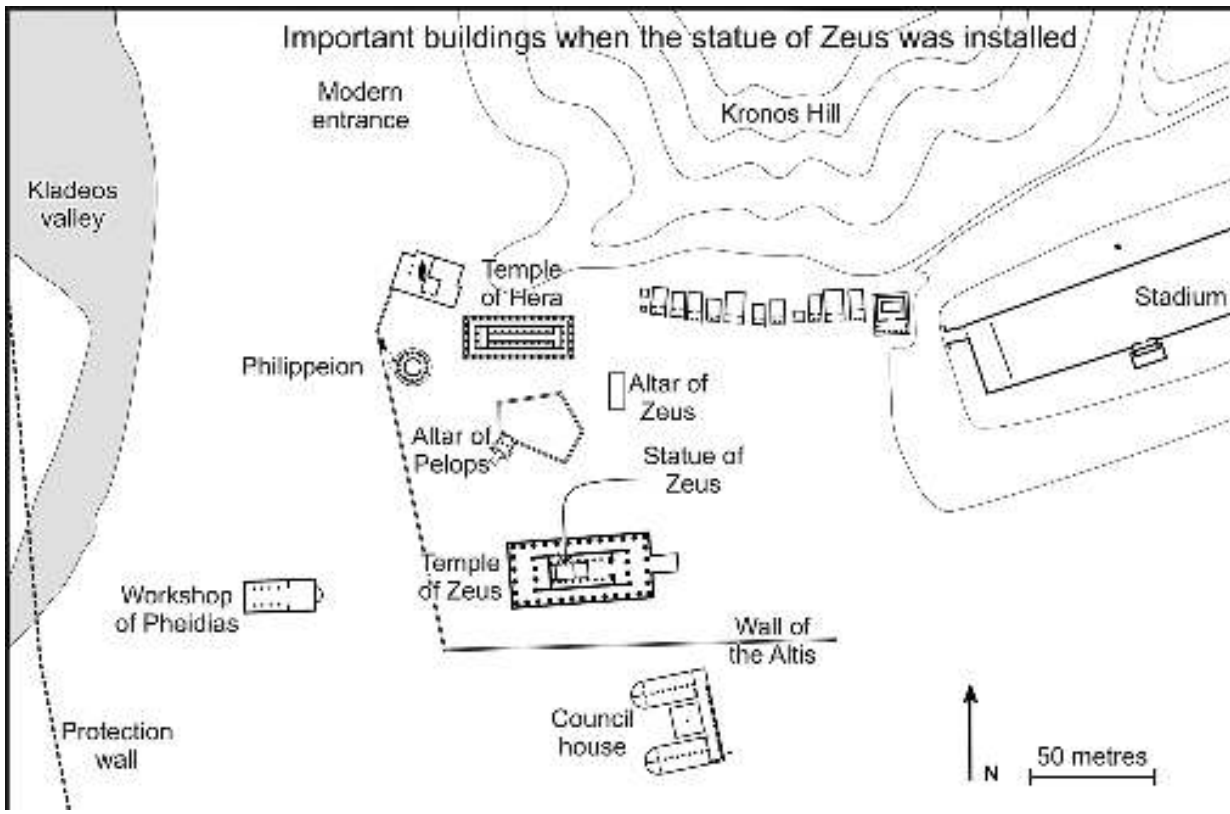


Figure 4-4: Construction at the Sanctuary of Olympia continued for almost two thousand years, from the Archaic to Roman periods, but here I show only the main buildings that were extant in 470 BCE when the Temple of Zeus was built. Map by author after Wikimedia Commons, Public Domain.

The temple of Zeus was the focus of the Olympia Sanctuary, which occupied a flat terrace between the Kladeos Stream and the Alpheios River (Figure 4-4, Figure 4-6, Plate 8a, Plate 9a). When the statue was set up, there were already other temples, the stadium and a hostel for officials—the athletes and spectators had to sleep outside! Development of the site continued long after the construction of the temple but it and other key buildings remained almost unaltered until the destruction of the sanctuary in the 4th century CE.

The sanctuary is still an impressive and beautiful site, enclosed by valleys and low hills, and verdant even in the hot and dry Greek summers (Plate 8a). This geography obviously influenced the wealth and power of Elis, the city that controlled the sanctuary for much of the time, but how did this landscape form? Natural processes were

significant early on but were augmented later by human activities such as deforestation and farming.

Olympia Basin and Terrace

Olympia lies in a broad sedimentary basin that started to form fifteen million years ago, when the whole region was stretched in a north-south direction and huge blocks of the crust subsided below sea level, rather like western Turkey during the same period (Figure 4-5; see Chapter 6 box 6-3: The Aegean Coast of Turkey).[161–162] Pebbles, sand, and mud were deposited in this shallow sea, where they accumulated along with marine shells and calcite mud. About two million years ago, regional geological forces changed so that the rocks of the region were lifted up above sea level and rapidly eroded by rivers to give the rounded hills that we see today around Olympia. The valley bottoms were filled with fertile soils, whose high clay content enabled them to retain water from winter rains into the summer, favouring agriculture and settlement of the region.[163] One such place was the future sanctuary of Olympia, where a small stream, the Kladeos, joins the Alpheios River, the largest in the Peloponnese.

The Olympia Terrace is a former floodplain of the Kladeos Stream formed five thousand years ago as a result of Neolithic farming in the hills to the north (Figure 4-6, Plate 8a).[164] Deforestation for cultivation exposed the soil to erosion, especially during winter storms. Mud and sand were washed into the stream and transported down to the future site of Olympia. There, the land flattened out and the stream meandered across the valley, depositing fertile sediments to make the Olympia Terrace. In antiquity, it would have been covered by olive, poplar, palm, and plane trees. But it is now dominated by conifers planted in the 19th century.

Then, as now, floodplains were popular for settlement as they were fertile and well-watered, even though they were also continually threatened by flooding and lateral movements of their streambeds: this

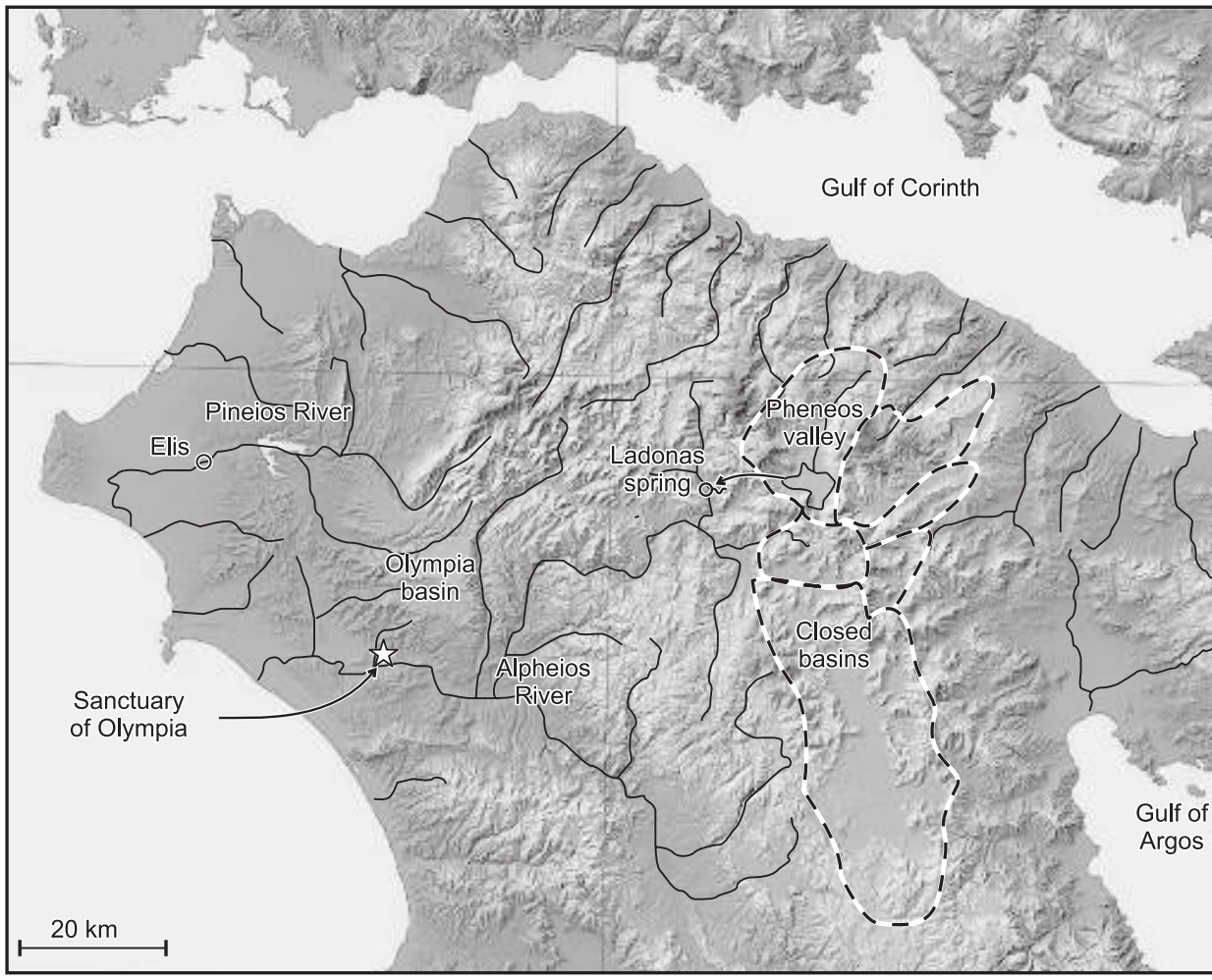


Figure 4-5: The Olympia Basin formed millions of years ago when north-south forces stretched the crust and broke it up along east-west faults. The low, rolling hills near Olympia contrast with the mountainous eastern Peloponnese. Here, closed hydrologic basins drain internally via caves and fissures to feed distant springs. Map by author after Wikipedia Commons, Public Domain; Morfis, A. and H. Zojer, 1985, "Karst Hydrogeology of the Central and Eastern Peloponnesus (Greece)," *Steirische Beiträge zur Hydrogeologie*, 37–38: 1–301; Fountoulis, I., I. Mariolakos, and I. Ladas, 2014, "Quaternary Basin Sedimentation and Geodynamics in SW Peloponnese (Greece) and Late Stage Uplift of Taygetos Mt. Bollettino di Geofisica Teorica ed Applicata," 55(2); Fountoulis, I. and I. Mariolakos, 2008, "Neotectonic Folds in the Central-Western Peloponnese, Greece," *Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften* 159(3): 485.

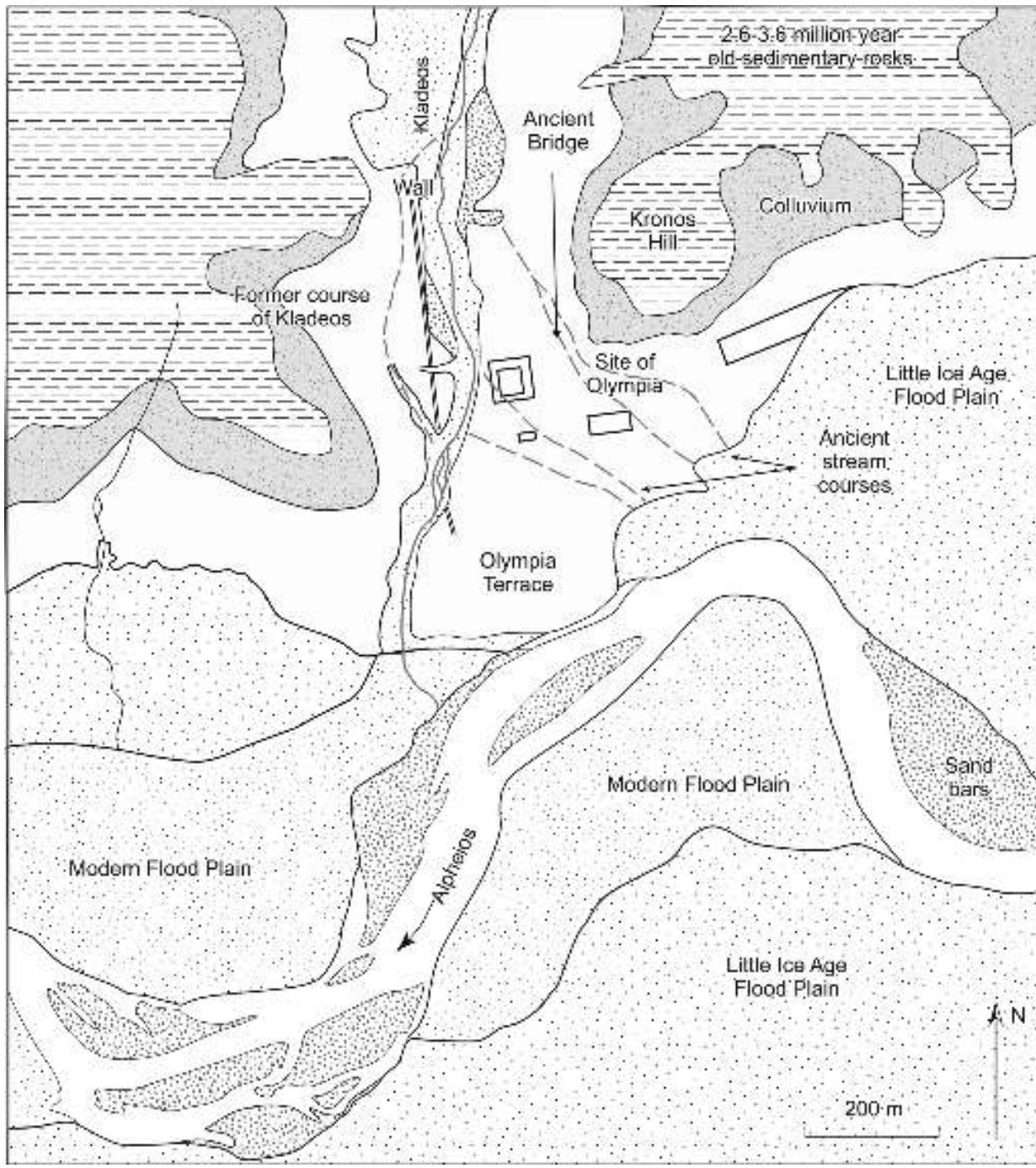


Figure 4-6: The sanctuary of Olympia lay on a river terrace formed by the Kladeos Stream and eroded by the Alpheios River. The surrounding hills of soft, young sedimentary rocks shed loose sediments called colluvium onto the Olympia Terrace. After the site was abandoned in the fifth century CE, the Kladeos Stream migrated across the site, burying it under more mud and sand. The floodplain of the Alpheios River is now quite narrow, as it was in antiquity but it was much wider during a wetter period called the *Little Ice Age* (1550–1850 CE) when the stadium was partly destroyed. Map by author after Fouache, E. and K. Pavlopoulos, 2010, "The Interplay between Environment and People from Neolithic to Classical Times in Greece and Albania," in *Landscapes and Societies: Selected Cases*, I.P. Martini and W. Chesworth, editors, Springer: Dordrecht.

was certainly the case for the Olympia Terrace. The Kladeos flowed across the floodplain between low banks it had built up by sedimentation. These levees would have been breached during major storms, changing the course of the stream in the process (see Chapter 3). This problem must have arisen early in the site's history, perhaps even during Mycenaean times (15th–10th centuries BCE), when a substantial wall 800 metres long and over 3 metres high was constructed to the west of the site to keep the stream away from the terrace (Figure 4-6). However, by the 2nd century BCE the stream flowed to the east of the wall across the ancient site, as shown by the remains of a bridge. During the 2nd and 3rd centuries CE, flooding of the site forced the Romans to repair the wall and restore the Kladeos streambed to its original position west of the wall. After the site was abandoned in the 5th century, the stream again returned eastward and buried the site in sediments, preserving the ruins until they were excavated in the 19th century. The stream now flows between the ancient wall and the site in a steep-sided valley that reduces the threat of flooding.

The Olympia Terrace was also threatened by sediments from another source: Kronos Hill, which is made of soft, unconsolidated sediments, easily eroded during winter storms into aprons of loose sand and mud called colluvium (Figure 4-6). These deposits encroached on the Olympia Terrace and must have been a problem in antiquity, as another wall was constructed to protect the site from this material. It seems to me that there may be an element of geomythology here in the naming of the hill: Kronos Hill was named after the absentee father of Zeus, whom he overthrew when he came of age. However, Kronos had his revenge in the form of the colluvium from his hill that every winter threatened to bury his son's sanctuary.

The Alpheios River

The Alpheios River that borders the Olympia sanctuary at its southern end is the most important in the Peloponnese, both for its length and

flow rate, and for its great natural, ecological, and cultural significance (Figure 4-5, Figure 4-6). This river is fed by runoff from the surrounding hills as well as water from huge springs in the peninsula's mountains. These springs maintain river flow during the long dry summers and may have also produced significant floods. They are particularly interesting because they form part of a special landscape called *karst* that is widespread in the Aegean region (Figure 4-7).[160]

The western part of the Peloponnese is an excellent example of a karst landscape, which develops where the bedrock is dominated by limestone or marble, a common situation in the Aegean region.[165] In these areas rainwater and snowmelt does not always drain into streams and rivers but may dive down into sinkholes and caves, to flow underground, reappearing at springs (Figure 4-7). This happens because calcite, the main mineral in these rocks, is soluble in rainwater. At the surface, large basins can develop, which are completely rimmed by hills with underground drainage at their base (Figure 4-7). Such basins make up a large proportion of the eastern Peloponnese (Figure 4-5): some basins drain eastwards to feed springs near and in the Gulf of Argos, whereas the Pheneos and other nearby basins feed springs to

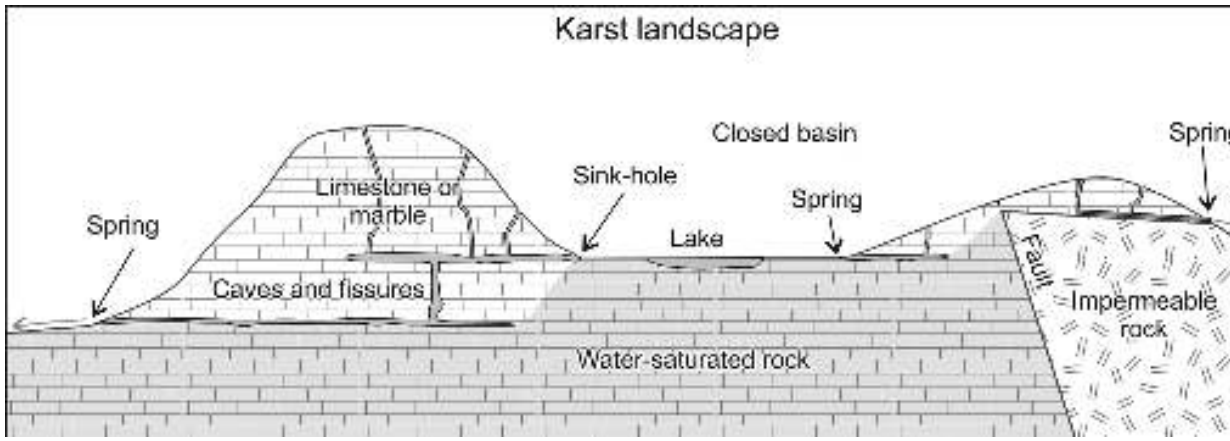


Figure 4-7: A karst landscape forms by the dissolution of limestone or marble. Here, rainwater and snowmelt may flow underground in fissures and caves, as well as over the surface. Commonly there are closed basins, which may be dry or host a lake. Water drains from the basin through a sinkhole or cave, and flows underground to reappear where the water table reaches the surface. Springs can also appear above a contact with an impermeable rock like schist or shale. Image by the author.

Box 4-3 Hades in the Peloponnese

The caves, sinkholes, and springs of the Peloponnese may have inspired the idea of Hades, the world of the dead, and the River Styx, which marked its boundary.[169,195] Herodotus says that the Styx flowed out of Hades near Pheneos: "It is a stream of small appearance, dropping from a cliff into a pool; a wall of stones runs around the pool. Nonakris, where this spring rises, is a city in Arcadia near Pheneos" (Histories 6.74.1, trans. Godley) and Pausanias remarked that the waters were toxic. The ancient Styx is thought to be the modern Mavroneri (*black water*) stream.[196] This stream may have acquired its adverse reputation from its taste: sulphide minerals commonly occur in limestone and their oxidation to soluble iron sulphates gave the water an astringent flavour and a sulphurous smell. However, although unpleasant, such waters are not toxic, and indeed many people consider that similar spa waters are good for you.

the west, which ultimately flow into the Alpheios River. This special landscape inspired many legends, such as the location of Hades, the realm of the dead (see box 4-3: Hades in the Peloponnese).

The Pheneos Valley is one of the most impressive of these closed basins (Plate 8b). Its steep walls descend to a flat floor that slopes gently to a sinkhole that drains the basin and feeds Ladonas Spring about 5 kilometres away. Such sinkholes are easily blocked by vegetation, rock falls, or human activities, and then the whole valley fills up with water until the increased pressure washes away the obstruction or the water overflows the basin's walls. The valley will then empty catastrophically, feeding a massive amount of water into the outlet spring. In this case, the flood would travel from Ladonas Spring down the Alpheios valley, past the site of Olympia. Eratosthenes first described these floods in the 3rd century BCE and established the connection between Pheneos Valley and Ladonas Spring.[166] Such floods may have eroded parts of the Olympia Terrace but as I mentioned before were not responsible for the site's burial. Such catastrophic floods may have also inspired

the story of the fifth labour of the Greek hero Heracles, the cleaning of the stables of King Augeas (see box 4-1: Cleaning King Augeas's Stables).

Water Supply

The ancient Olympic Games started at the full moon closest to the summer solstice (June 21), in the driest part of the year. The large number of spectators, perhaps up to forty thousand, and animals must have not only taxed the water supply but also polluted the rivers. Pliny alludes to this in an improbable story: "The following phenomena too are very wonderful: the Arethusa Spring at Syracuse [in Sicily] smells of dung during the Olympian Games, a likely thing, for the Alpheios River crosses to that island under the sea bed" (*Natural History*, Book 31, Section 30). This is clearly a geomyth, as there is 700 kilometres of sea between the Alpheios River and the Arethusa Spring. However, there are karst springs in the Gulf of Argos that do flow under the seabed to issue a few hundred metres offshore, so this story may have originated as an extension of actual observations (Figure 4-5).[167]

Initially, water for the games was drawn from the river and shallow pits sunk into the river sediments. From about 700 BCE, wells were dug closer to the sacred site and these are the earliest archaeological evidence that significant numbers of visitors attended the games. Another early water source is suggested by a lion fountain found near the 7th century BCE Hera temple.[168] It may have been one a pair that were fed by a spring, perhaps at the base of Kronos Hill or from farther up the Kladeos valley. If such a water source existed, then it may have been associated with an oracle of Zeus, which predated the games as the main celebration of the god.[169] However, as water sources near the sanctuary became overexploited, the water table was drawn down and the water became brackish, probably because of salts extracted from marine sediments under the freshwater lens at the surface.

In 157 BCE, the Roman senator Herodes Atticus decided to alleviate this problem by paying for the construction of an aqueduct three kilometres long. It started at natural springs in the low hills to the northeast, and crossed the south side of Kronos Hill to feed a magnificent fountain and basin in the sanctuary (Figure 4-14). The aqueduct was made of ceramic pipes or a lined channel cut into the hillside and very little remains now to show its original course. The springs that fed the aqueduct were not karstic like Ladonas Spring but issued from the base of a layer of conglomerate that caps the hills to the northeast. Winter rain penetrated between the pebbles of this loose, but erosion-resistant rock, and descended until it met the underlying sand and clay-rich rocks. These were less permeable so the water was forced to flow along this clayey surface, emerging finally at the springs.

I've talked about the overall structure of the region and its hydrology, but what about the stone used to make the temple of Zeus and other buildings in the sanctuary?

Stone

The temple of Zeus, and most of the other buildings of Olympia, were constructed of a shelly limestone that is poorly cemented and full of holes (Figure 4-8). This rock is dominated by fossil cockle shells, which grew in shallow waters and were sometimes thrown up onto beaches during storms. It is geologically young, about three million years old, and was never deeply buried by other rocks, and hence never subjected to compaction and recrystallization, which would have transformed it into a stronger material (see Chapter 7). It surprises many people that such a poor-quality material was used to make such an important building. The problem was that the closest sources of hard limestone were in the mountains to the east and it was difficult to transport material overland or up the Alpheios River to Olympia.

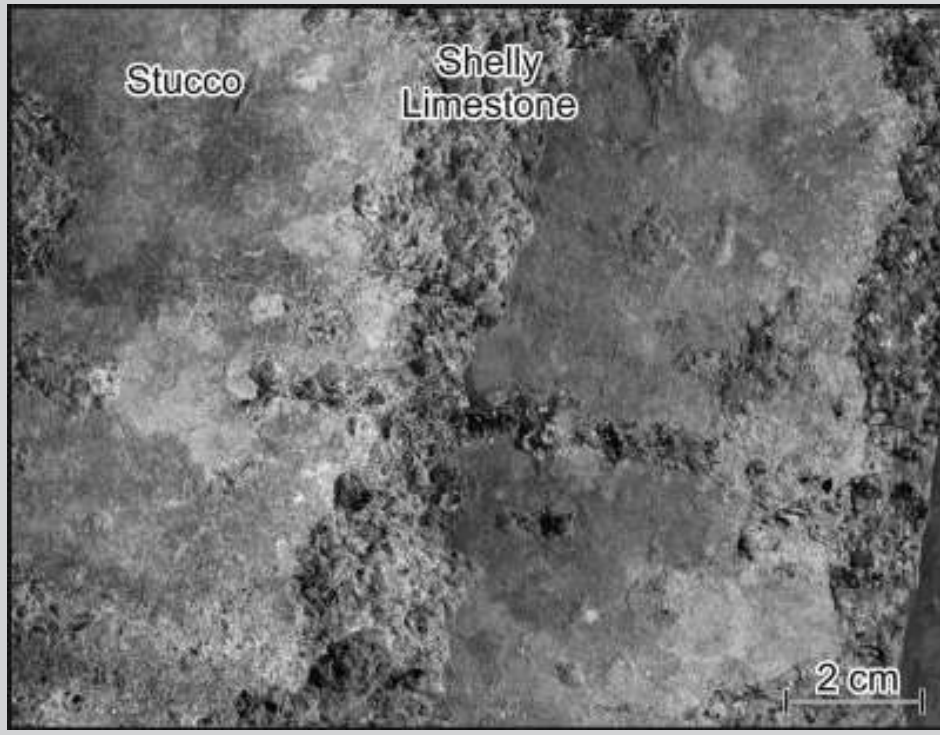
This shelly limestone did have its advantages: it could be cut to shape fast and was available from outcrops and blocks on the opposite

Figure 4-8: Most of Olympia's buildings, including the temple of Zeus, were built with a porous, shelly limestone. Photo courtesy of the author.

bank of the Alpheios (Curtis and Adler, 1892). There, it occurred as layers within sandy rocks similar to those that make up Kronos Hill. Much stone was likely obtained from loose blocks liberated from the bedrock by the river. There may also have been quarries along the river banks that have now been removed by erosion. The rough surface of the columns and walls of the temple were finished with a smooth layer of stucco to give the impression of marble or limestone and make them more resistant to weathering (see box 4-4: Stucco and Frescoes).

Sculptures and roof tiles of the temple were made of white marble. I'll talk about marble in more detail in Chapter 5, but fundamentally it is limestone transformed by heat and pressure deep in the earth. The early sculptures and tiles were made of marble from Paros Island. This luxurious material was translucent and expensive as it was mined underground.[170] Later replacements were made of cheaper marble from

Box 4-4 Stucco and Frescoes



Stucco on limestone column. Photo courtesy of the author.

The columns and blocks were finished with stucco, a plaster or mortar made from limestone or marble. Both rocks are made of carbonate minerals, usually calcite ($CaCO_3$). When the rock is heated in a furnace to more than 825°C, calcite loses carbon dioxide to become *burnt* lime (CaO). This is cooled and mixed with water to make slaked lime mud ($Ca[OH]_2$), which was applied to surfaces. Over time, the weak calcium hydroxide plaster adsorbs carbon dioxide from the atmosphere to form calcite crystals that are much harder. This chemical reaction is also the principle of fresco painting: paint is adsorbed into the surface of the damp calcium hydroxide plaster and sealed in when calcite is formed. I should mention that Roman pozzolanic concrete and modern cement ("Portland cement") have different compositions from the stucco described earlier.

The best raw material for making stucco is marble. Most limestones have some clay in them and this bakes to a ceramic during the processing, making the burnt lime difficult to crush. Marble

does not have this problem as it has already been baked naturally when it was metamorphosed from limestone and the clays were converted into new minerals (see Chapter 6). This is why marble from ancient ruins, such as the Mausoleum, was favoured for making lime for stucco and mortar.

Mt. Penteli near Athens. Perhaps an earthquake damaged the sculptures and roof and repairs had to be done on a budget or in a hurry.

The base of the Zeus statue, and the basin in front of it, were made of a dark, fine-grained limestone from Eleusis.[170] This rock owes its colour to specks of bitumen, a natural hydrocarbon derived from ancient plant remains (see Chapter 3). It is commonly called "black marble," but it is not marble by geological definition as it has never been subjected to high temperatures and pressures, which would have produced visibly larger crystals of calcite and removed most of the bitumen.

The statue was covered with gold and ivory, valuable materials that were not sourced in this region. Trade over long distances was well established early in antiquity, and we know a lot about where such resources came from and how they formed. I will start with gold, then and now the very definition of luxury and wealth.

Gold

The garments of Zeus were made of gold. However, the gold was not in thick plates, such as those applied to Pheidias's Athena in the Parthenon, because the Zeus statue was never intended as a repository of wealth but only to glorify the god. Indeed, gilded bronze may have been used instead, as was the case for other statues.

Gold is regarded as the noblest of metals because it does not tarnish or corrode readily. This lack of reactivity explains why the most

common ore mineral is metallic gold itself and not other gold-bearing minerals (Plate 9b). Natural gold metal is not usually pure and contains some proportion of silver, commonly 5–20%, which gives the metal a paler colour. If there was more than 20% silver, then the pale-yellow alloy was called electrum, so named because the colour was thought to resemble amber, *elektron* in ancient Greek (see Chapter 6, box 6-2: Money and Minting). The purity of gold was checked by rubbing the metal on a dark, fine-grained stone surface ("touchstone") and noting the colour of the streak left behind.

Gold has a long history of use in many places in the world, starting seven thousand years ago in what is now Bulgaria. The first type of deposit to be exploited were accumulations of gold flakes and nuggets in riverbeds called placers (Figure 4-9).[171,172] The process starts with the liberation of gold grains from the ore by weathering and its transport downslope to streams and rivers. These grains are much denser than the mud, sand, and gravel also transported by the river; hence, they will follow the shortest route and accumulate where the river flows most slowly (Figure 4-9). Particularly favourable areas are the gravel bars that line the inside of river bends and tranquil pools behind boulders in the riverbed.

This is not the whole story, however, because interestingly placer gold is commonly purer than gold in the original ore, especially when far from the source, and may occur in much larger masses called nuggets. One explanation is that gold grains are not purely a residue of weathering but have grown in place in the streambed or the soil. It may seem surprising but gold is very slightly soluble in water and can plate out onto existing grains to make nuggets if there is a change in the composition of the water. It is also possible that bacteria participate in the reaction: we know that they can cause the precipitation of metals from watery solutions and some gold grains appear to be fossilized bacteria, in which the cell walls have been replaced by gold.

In antiquity, miners separated gold grains from placer sands or powdered ore by using a pan or a sluice, as they do now. A pan is just a

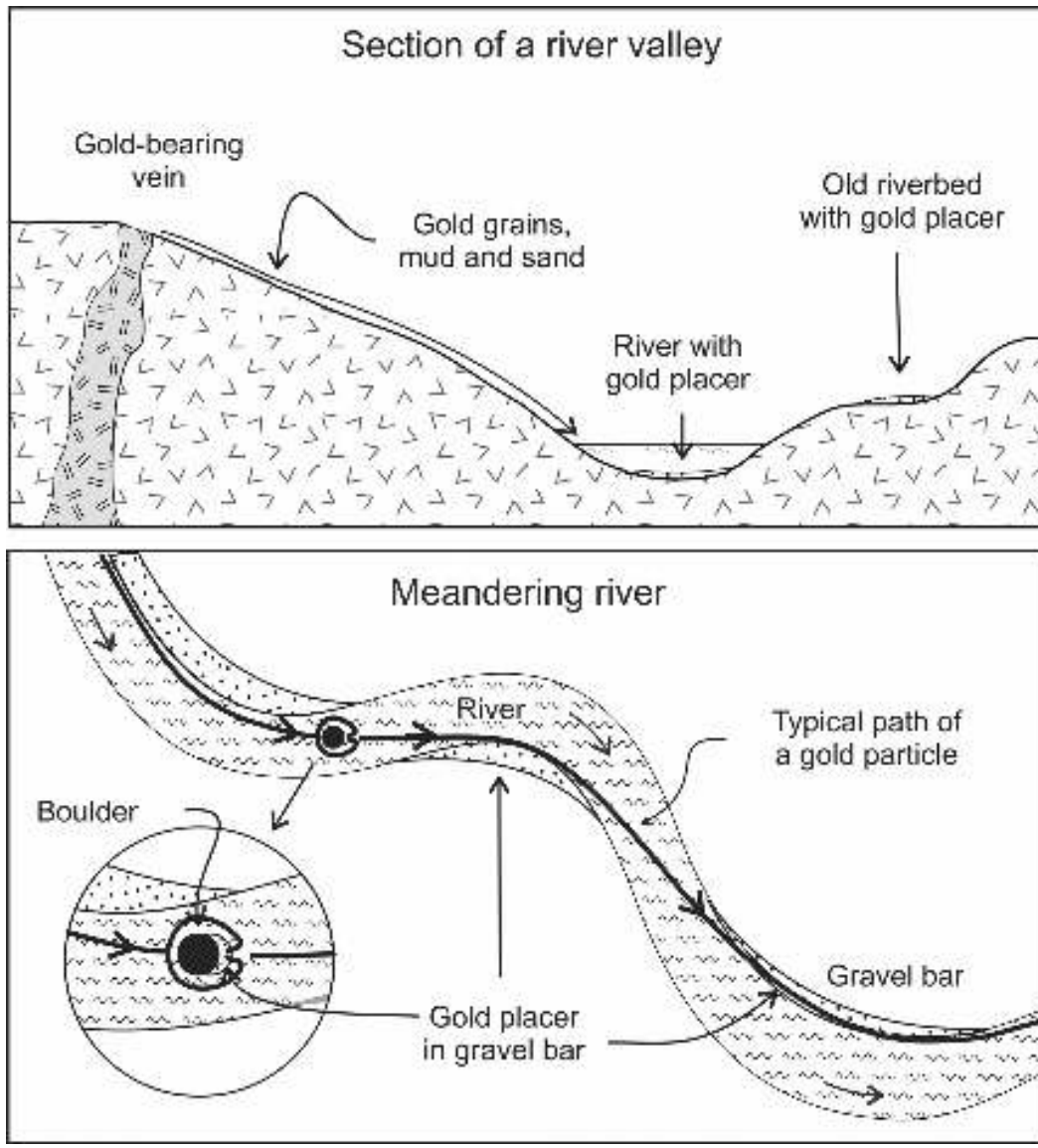


Figure 4-9: Gold grains weather out from a vein and are washed down the slope to the river together with mud and sand. Here, the heavier gold grains will accumulate in the riverbed making placer deposits where the water flows slowest. Images by author after Thornton, M., 1975, *Dredging for Gold: The Gold Divers' Handbook: An Illustrated Guide to the Hobby of Underwater Gold Prospecting*. Keene Industries: Northridge, California.

shallow dish 20 to 30 centimetres in diameter. The gold-bearing sediments are put in the pan and it is gently swirled just below the water surface. Lighter sediment grains are washed over the edge, leaving behind the gold in the bottom of the pan. It is cheap and easy to use but can only handle small amounts of material at a time. For larger

operations, water is diverted into an artificial channel made of wood lined with ridges called a sluice. Sediments are shovelled into the sluice and the water carries away the lighter grains, leaving the gold particles trapped behind the ridges. In antiquity, sluices were lined with sheepskins to collect the gold, a practice that continued until the early 20th century in isolated places around the Black Sea. Could the use of sheepskins have inspired the legend of the *Golden Fleece* of Jason and the Argonauts?

Once the placer deposits had been exhausted, interest turned to the original gold-bearing rocks themselves. At that time the most important sources were rare quartz veins in which gold was readily visible as grains up to 1 millimetre long (Plate 9b). Such lode gold deposits originated from hot, watery fluids deep in the crust, that contained sulphur, carbon dioxide, and other compounds. These solutions leached gold and silica from the surrounding rocks and rose to the surface along faults—cracks in the crust. Decreasing temperatures and pressures, as well as loss of carbon dioxide and other gasses, forced quartz and gold to precipitate along the walls of the fault, commonly along with carbonate minerals and pyrite (FeS_2, *Fool's gold*). Gold is easy to distinguish from pyrite as it is malleable instead of fragile. In addition, it leaves a yellow trace on a rough surface whereas pyrite has a dark brown streak. The general rule for identifying gold is that if you have to ask yourself, "Is this really gold?," then it is not.

We do not know much about gold mining when the statue was made but we do have an account from the first century BCE written by Diodorus Siculus (*The Library of History*, Book 3.12.1), in which he describes gold mining in Nubia by slaves and prisoners. They first weakened the rock face by setting fires and then mined the ore by pounding the rock with iron hammers. The blocks were further crushed to a few millimetres with iron pestles in stone mortars and finally ground to a flour-like consistency. Finally, gold was recovered by washing away the lighter minerals on inclined tables. His report of

the use of slaves in the mines has been questioned but he did have a clear vision of the whole industry: "The working for gold, as it is carried on at the furthermost borders of Egypt, is effected through all the extensive labours here described; for nature herself, in my opinion, makes it clear that the production of gold is laborious, the guarding of it is difficult, the zest for it is very great, and its use is half-way between pleasure and pain." It seems clear to me that those who experienced the pleasure of gold were not those who suffered the pain of extracting it!

Gold deposits are found in many different parts of the world, especially where there are metamorphic and igneous rocks. In the Aegean region, gold was initially exploited in Macedonia and Thrace (Northern Greece), and on the island of Thasos but these sites were exhausted early in antiquity[170] (Figure 4-10). At the time of the statue, the most important source of gold was probably Lydia, on the Mediterranean coast of Turkey east of Izmir.

The Lydian placer deposits were concentrated along the Pactolus River (modern *Sart Çayı*), where exploitation started in the 7th century BCE and continued intensely for about seven hundred years. This major deposit owed its richness to reworking by the river of much older placers, some of which are still preserved in parts of the valley as a loosely cemented conglomerate.[173] According to myth, the god Dionysus gave King Midas of Lydia a wish and he asked that all he touched would be changed into gold. However, he soon realized that he could no longer eat or drink and asked for the gift to be withdrawn. He was told to wash in the Pactolus River, whereupon his "gift" passed into the river and changed the sand into gold. Although a myth, this story recalls the geological process of solution and precipitation of gold on nuggets, possibly aided by living organisms like bacteria (not kings).

Gold does not need smelting as the ore is the metal itself but it may need processing to separate it from other metals, particularly silver and copper. The melting temperature of gold is quite high, 1063°C, and

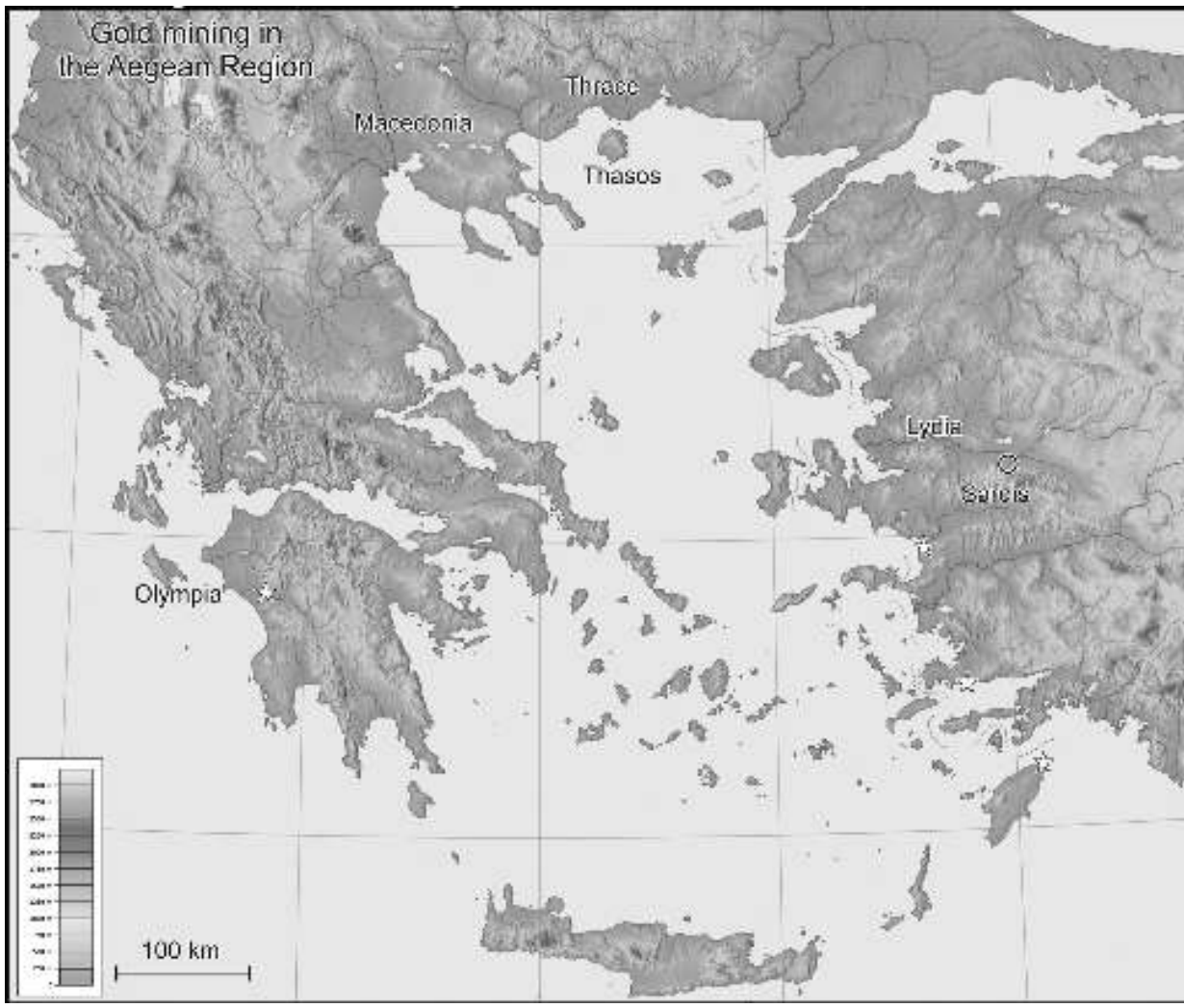


Figure 4-10: It is difficult to determine the original source of the gold used to make the statue, but it probably came from Lydia. The famously rich Pactolus River is a small stream that flows north to Sardis. Map by the author.

is not significantly lowered by the presence of silver, which melts at 961°C, so a furnace must be fueled with charcoal and oxidized with air blown in by bellows, as for smelting copper and iron. The molten gold can be poured directly into moulds or cast and processed further to remove silver and other impurities (see Chapter 6, box 6-2: Money and Minting).

The Zeus statue was clothed in gold but its skin was of ivory, thus linking the god to a powerful, semi-mythical animal. It was the ideal material: white and hard, and easy to carve and polish. There were no other materials available at that time that could compare.

Ivory

Most ivory used in ancient Greece was from elephant's tusks, although the teeth of boar and hippopotamus were also used occasionally. Tusks are modified continuously growing teeth and are mostly made of dentine, which forms the tusks' core under a protective coat of enamel. Dentine is a complex material composed of 70% of hydroxylapatite ($Ca_5[PO_4]_3[OH]$), 20% organic material and 10% water (Figure 4-11).[174] Dentine owes its strength and carvability to its composite nature—pure hydroxylapatite is brittle but cracks in ivory are stopped where they run from the crystals into the organic part of the material. The individual crystals are tiny tablets, measuring 30 by 3 nanometres, and are surrounded by collagen fibres.

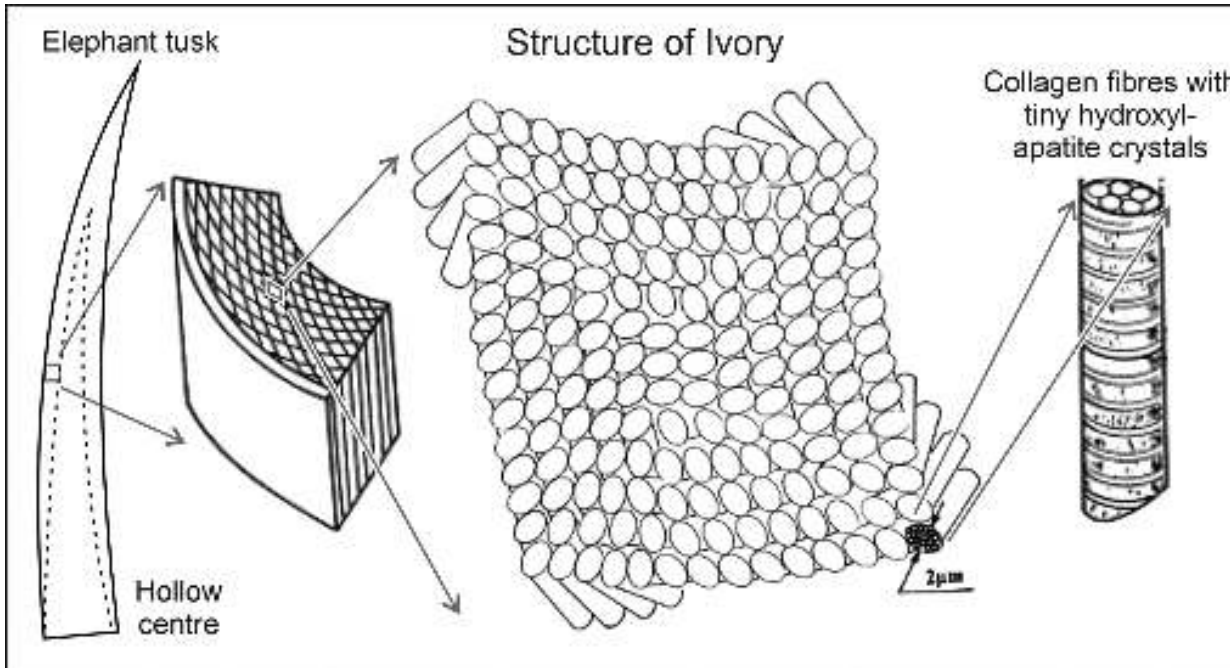


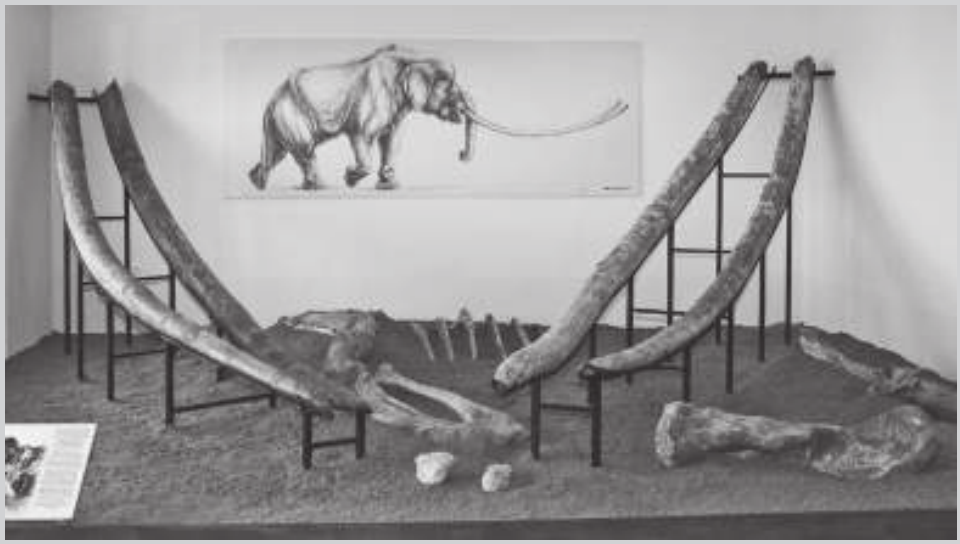
Figure 4-11: Ivory owes its strength, hardness, and carvability to its complex, hierarchical structure. A slice of ivory from a tusk has two sets of intersecting lines that define a series of lozenges. Within each lozenge, there are bundles of fibres with variable orientations. Each bundle is made of collagen protein chains separated by hydroxylapatite crystals. Image by author after Su, X.W. and F.Z. Cui, 1999, "Hierarchical Structure of Ivory: From Nanometer to Centimeter," *Materials Science and Engineering C*. 7(1): 19–29.

The ivory pieces of small statues could be carved directly from tusks but the huge area of ivory on the Zeus statue necessitated a different approach.[175] It is thought that specialized workers were able to saw, slice, or peel tusks to make large, thin sheets. These were made flexible by soaking in vinegar, which partly dissolved the mineral component of the ivory. The development of caries in teeth is a chemically similar process. The softened ivory sheets could then be pressed onto moulds and left to dry.

The three different living species of elephant could have served as ivory sources in antiquity.[154] The smallest was the forest elephant (*Loxodonta cyclotis*), which is now confined to the Congo basin. However, during the Bronze Age, forest elephants roamed from Morocco to Libya and along the coasts of the Red Sea and the Gulf of Aden: at the time of the statue's construction, they were still abundant in Sudan. The larger bush elephant (*Loxodonta africana*) is now widespread in pockets throughout tropical and southern Africa but it does not appear that the Mediterranean world was aware of this species, although its ivory may have been traded. Finally, the Asian (Indian) elephant (*Elephas maximus*), although now confined to India and Southeast Asia, probably ranged to Syria until the 8th century BCE. It is intermediate in size between the forest and bush elephants but only the males have tusks. Though Pausanias mentions Asian elephants, the ivory used in the Zeus statue most probably came from forest elephants in Sudan and was traded down the Nile or the Red Sea to the Mediterranean. Fossilized ivory was and is found in Greece but was little used in antiquity as it is too brittle to carve (see box 4-5: Fossil Ivory).

Fresh ivory contains water and will crack if it is allowed to dry out. This problem was well-known in antiquity and that was why there was a basin filled with olive oil in front of the statue. However, the oil vapours did not reduce cracking: it would have been better to have put the oil on the ivory and water in the basin.

Box 4-5 Fossil Ivory



Museum display of mastodon remains from Milla, Greece. Vlachos, E., et al., 2018, The Paradise Lost of Milia (Grevena, Greece; Late Pliocene, Early Villafranchian, MN15/MN16a): Faunal Composition and Diversity. *Quaternary* 1(2): 13.

There was also a local source of ivory: the fossilized tusks of mammoths and mastodons that lived in the Aegean region for millions of years before their extinction about ten thousand years ago.[197] Many bones and tusks of these animals have been found along the Alpheios River and elsewhere in recent times. We know that ancient people were aware of these tusks, they were difficult to miss as some were five metres long, and they were displayed in collections of curiosities, proto-museums, along with the fossilized bones of other large animals.[18] Indeed, the huge size of some of these bones, and their similarities with the smaller bones of modern animals, may have inspired myths of an ancient race of giant people and gods.[18] Indeed, Pausanias mentions that a sacred relict of King Pelops, his shoulder blade, used to be kept in the sanctuary and it has been proposed that this was the scapular of a mammoth. The tusks, however, were essentially decorative as fossil ivory is brittle and difficult to carve: the fine hydroxylapatite crystals have recrystallized, expelling most of the organic matter, so that fractures in the crystals are not stopped by contact with the more flexible materials.

Formed Glass

The descriptions of the statue by Pausanias mentioned gold and ivory as the main construction materials but excavations near Pheidias's workshop revealed many fragments of glass (Figure 4-12). The excavators also found clay moulds, whose size and shape suggest that they were used to shape glass for the drapery of a figure. Molten glass may have been poured into the moulds, but it more likely that glass was formed by "sagging."[176] In this process, a glass sheet is put on top of the mould and the whole ensemble is heated in a furnace whereupon the glass sags into the undulations of the mould.

The moulds appear to be for a figure three times life-size. If this figure was part of the Zeus statue group, then it may have been the Nike that Zeus held in his hand. In this case, most reconstructions of the statue have underestimated the size of the Nike by a factor of two (Figure 4-1). However, there is another problem—Pausanias clearly states that the Nike statue was made of ivory and gold. A possible way of reconciling Pausanias's observations with these excavation materials is the glass drapery was backed with gold, in a similar way to the Byzantine mosaics

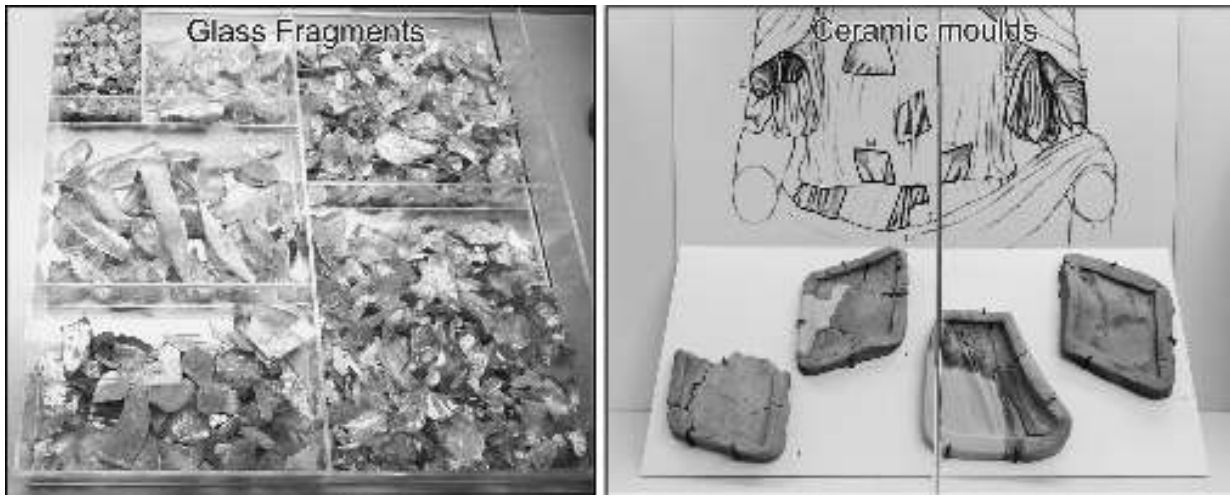


Figure 4-12: Excavation of Pheidias's workshop revealed abundant fragments of glass now in the Olympia Museum. Ceramic moulds were also found and were probably used to form glass for the drapery of a large figure. Photos courtesy of the author.

that were made much later.[154] Of course, the glass fragments may have belonged to another, unknown statue, made at the same time as the Zeus statue and in the same workshop. Or that it was an experiment that failed and was replaced but a more conventional ivory and gold Nike figure. We know that manufactured glass was not a new material in the 5th century BCE, having already been used for over a thousand years but this seems to be the first time that an attempt was made to use it on such a large scale; hence there were many possibilities for failure.[177]

Glass is a material that has some of the physical characteristics of both solids and liquids.[176,178] Glass clearly has the strength of a solid but the internal arrangement of atoms is random, as in a liquid. Glass forms when a liquid is cooled so fast that crystals cannot grow and occurs naturally as the rock obsidian. Obsidian tools were used extensively in Neolithic times and continued to be important after the discovery of bronze and steel because they were cheaper than metal tools. Indeed, fragments of obsidian were found in Pheidias's workshop although it is not clear if they were used as tools or material to decorate the statue. In the Aegean region, the main source of obsidian was Melos Island.[179] The volcanic eruptions there predate human occupation, so there were no observations of how obsidian was formed.

Manufactured glass was probably discovered by accident: a strong wind may have made a particularly hot fire that fused soda from the wood ash with silica from a sandy fire pit. The result was a frit—a partly fused porous glassy mass. Afterwards, glass was made deliberately from a mixture of quartz sand (SiO_2) and materials containing soda (Na_2O) and lime (CaO). Very high temperatures are necessary to melt pure silica, 1700°C, so soda is added to reduce the melting temperature to a more reasonable 1000 °C. Such a simple soda-silica glass is soluble in water, so lime is added as a stabilizer. The reaction between the pure ingredients is slow, so lumps of old glass are generally added to speed up the process: they melt at lower temperatures and the resulting liquid then reacts with the other materials.

In antiquity, the main ingredient of glass was quartz beach sand. Some beaches were particularly favoured as they had a high content

of shells, which contained lime in the form of calcite or aragonite (both are $CaCO_3$). The Roman writer Pliny mentions a source near the Belus River, just north of Haifa, Israel, and there were undoubtedly other sources.[180,181] Soda was usually obtained from natural mineral deposits, rather than wood ash. The most likely source was the alkali Natrun Lakes in Egypt (see Chapter 2), where it occurs in the mineral trona ($Na_3[CO_3][HCO_3]\cdot 2H_2O$).

In antiquity, glass was commonly manufactured in large blocks, which were broken up and transported as fragments, to be remelted on site.[182] These glass factories were located either near a sand source or the soda source in Egypt. However, we have not yet found factories of the right age to have produced glass for the statue's Nike.

The statue remained in the temple for over eight hundred years and must have been repaired and restored many times. However, it could not resist changes brought about by the arrival of a new religion and the consequent demise of the games honouring Zeus.

The Demise and Destruction

When Roman Emperors converted to Christianity, they repressed the old religions and their symbols, a story that has been repeated many times in history, most recently in Iraq at the site of Nineveh. Constantine (272–337 CE) started it by ordering the removal of gold and other precious metals, which meant that the underlying wood and plaster making up the body of the sculpture would have been exposed. I am sure that this situation was untenable so Zeus's golden clothes may have been replaced by actual cloth, although it would have been more difficult to replace his golden garland. In 391 CE, Theodosius I closed the temples of the sanctuary, which led to a steep decline in the prestige of the games. During the following century, the economic basis of the sanctuary was strongly affected by the collapse of the Western Roman Empire, which forced a migration from the land to the towns.

Figure 4-13: The columns of the temple of Zeus collapsed before 565 CE and fell like dominos on the ground. They may have fallen during an earthquake in 522 or 551 CE, or they may have been deliberately toppled so that stone and metal clamps from the inner walls could be removed. Photo courtesy of the author.

Some time after the closure of the temple, the eunuch Lausos, an important imperial official, took the remains of the statue to his palace in Constantinople (now Istanbul) to complement his collection of antiquities.[183] The collection was conserved after his death but destroyed in 475 CE when much of the city was burnt accidentally.[184] The temple did not last as long as the statue: it burnt in 426 CE, possibly on the orders of Theodosius II. By 565 CE, the walls and the columns were no longer standing but it is not clear if they fell during an earthquake or were deliberately toppled (Figure 4-13).

Olympia was certainly susceptible to earthquakes, like most of the Aegean region (see Chapter 8). Relatively large earthquakes occurred to the west, along the Hellenic trough and to the north along the

Corinthian Gulf. Despite their distance, some of these events could have had significant effects at Olympia, because of the loose river sediments under the site, which can resonate like a bell during earthquakes, and thus amplify destructive ground movements. In this way, the columns could have brought down by relatively distant known earthquakes in 522 or 551 CE.[185]

The ancient builders certainly knew of the destructive force of earthquakes and tried to make their buildings as resilient as possible. In the walls, they bound stone blocks together using clamps of iron or bronze set in holes with molten lead. This was certainly quite efficient, especially for smaller tremors. Ironically, many temples were destroyed in later times to recover the metal in those clamps. Curiously enough, there was very little effort made to stabilize the columns: the small holes in the centre of the column drums (Figure 4-13) were used more for construction purposes. The pins of wood or bronze that were put into them to align the column sections would have provided little resistance to the forces produced during an earthquake. Perhaps it was felt that as the columns were unusually wide for their height they could resist seismically induced shaking.

However, it is also possible that the temple was not destroyed accidentally but deliberately so that the stone and metal clamps in the walls could be looted: the columns all appear to have fallen outwards, which would not be expected if they had been toppled by the movements of an earthquake. It would take considerable force to bring them down, perhaps several dozen oxen or horses but it would have been possible.[186] All that we can be sure of is that all the blocks from the inner walls were removed.

The sanctuary was abandoned shortly after the temple collapsed, but the site continued as a settlement, later occupied by incoming Slavic populations during the 6th to 7th centuries. From the 8th to the 12th centuries, the Kladeos Stream deposited sandy sediments in the valley and over the site, burying the remains to a depth of 6 metres and largely preserving it from erosion until the start of archaeological excavations in 1875 (Figure 4-13).[187] Archaeologists and earth scientists

have long discussed the origin of these sediments, with explanations that cover a wide range of timescales: although geologists traditionally favour long-term processes, which they interpret by looking at modern environments, rapid events do occur and can be important. The spectacular nature of such catastrophes also means that they attract more public attention than slower processes.

One clue to the origin of the sediments may be the presence of recent marine shells at a site that is now 15 kilometres from the sea. One catastrophic explanation would have these sediments deposited by one or more tsunamis, produced by fault movements somewhere in the Ionian Sea to the west, probably along a major plate boundary[188,189] (see Chapter 8). The tsunamis would have swept up the Alpheios valley, crossed the alluvial plains, breached the Flokas-Pelopio ridge to the east, flowed into the Kladeos valley and down to Olympia, where they ponded and deposited the sediments (Figure 4-14). The Flokas-Pelopio ridge is high, 60 metres at its lowest but perhaps the tsunami was amplified sufficiently by the shape of the basin to overtop this ridge. Shells in the sediments have been dated using carbon-14 and are approximately the same age as that of the earthquake that may have knocked down the temple columns, which could have produced a tsunami. However, there is no written evidence for these tsunamis. This may be because very few documents survive form this period or that truly catastrophic events are rapidly erased from the collective memory. Remember that we only have one description of the destruction of Pompeii in 79 CE, and that was not from a survivor but a letter in response to a historian's request for information on a general who perished during the eruption.

There are other explanations of the site's burial that invoke rather more mundane but perhaps more likely causes such as societal changes. A period of particularly cold weather during the 6th and 7th centuries set people in motion and this region was settled anew by Slavic farmers who burned and cleared the land for cultivation and pasture.[190] The exposed soil was washed into the streams during winter storms and the fast-flowing muddy waters carried the sediments as far

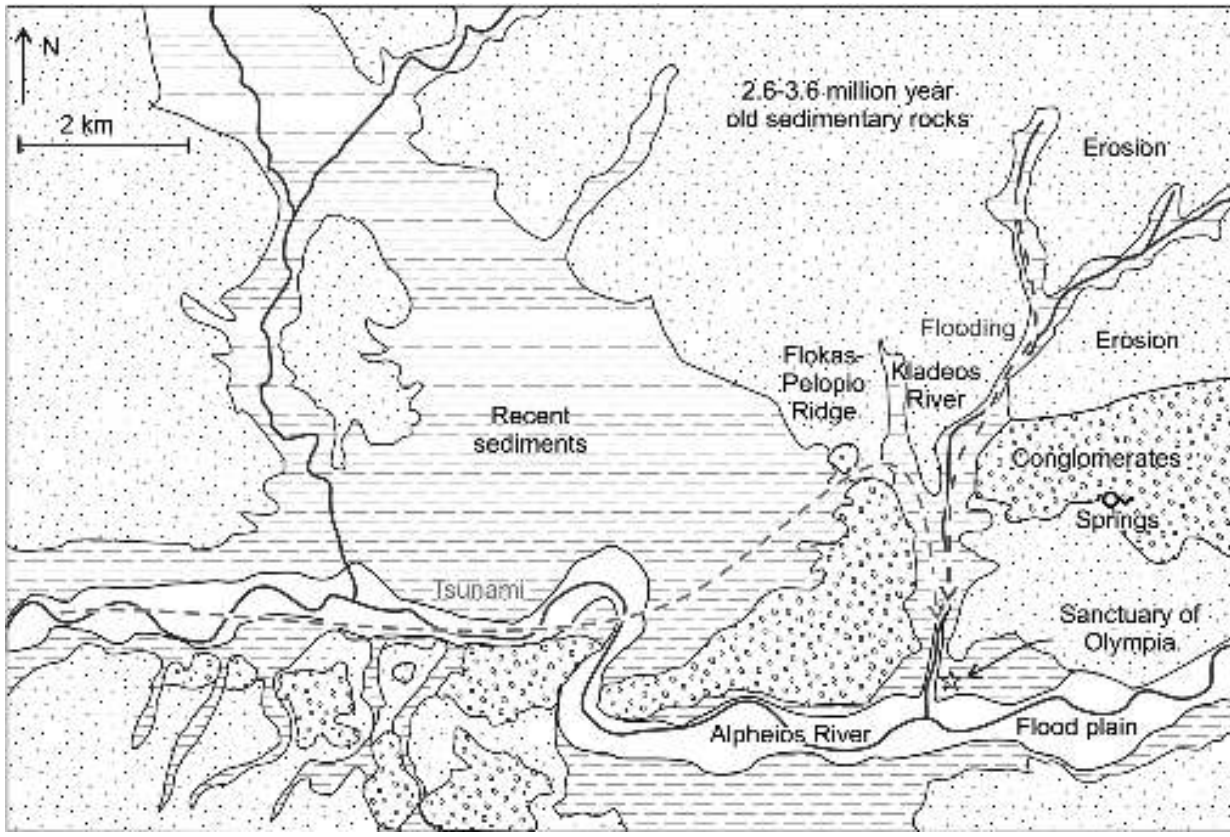


Figure 4-14: This geological map of part of the Olympia Basin shows how the sanctuary of Olympia may have been buried by sediments after it was abandoned. One possibility is successive tsunamis that came up the Alpheios valley, breached the Flokas-Pelopio ridge and descended the Kladeos valley. A more likely scenario is that flooding eroded the soft sedimentary rocks on the hills to the north and deposited them beside the Kladeos stream. Springs that fed the Olympia aqueduct emerge from the base of the conglomerates. Map by author after IGME Olympia Sheet, 1982.

as the Kladeos valley (Figure 4-14). Here, the water slowed down and meandered across the valley bottom depositing the sediments in a terrace. The marine shells mentioned before would then have simply been redeposited from older sediments. It is somewhat ironic that the Olympia sanctuary was built on a similar river terrace produced about five thousand years previously during a Neolithic cycle of settlement and erosion (Figure 4-6).[191]

Climatic and cultural changes since the mediaeval period caused other modifications to the geography of the Olympia Basin. From 1550 to 1850 CE the global climate was slightly cooler and wetter, a period called the "Little Ice Age." The increased frequency of flooding

made the river change from its former meandering form to a braided riverbed, in which the river spread out over a wide zone of gravel in the valley (Plate 9a). It may have been then that the stadium was eroded and the Kladeos Stream cut its present valley into the terrace.[164,187] Since then the climate has become drier and the river has returned to meandering across a narrower valley (Figure 4-6). During the 20th century, a new population exodus promoted revegetation and reduced erosion. However, this environment is now more susceptible to forest fires, which the authorities have tried to control by the installation of rather ugly sprinkler towers around the site.

Although the site never completely disappeared, partial burial made it difficult to appreciate its importance. The first published description of the site was by the English traveller Richard Chandler in 1766:[93] "The ruin, which we had seen in the evening, we found to be the walls of the cell of a very large temple, standing many feet high and well-built, the stones all injured, and manifesting the labour of persons, who have endeavoured by boring to get at the metal, with which they were cemented. From a massive capital remaining it was [apparent] that the edifice had been of the Doric order. At a distance before it was a deep hollow, with stagnant water and brickwork, where, it is imagined, was the Stadium. Round about are scattered remnants of brick buildings, and vestiges of stone walls." The first serious excavations were started in 1875 by German archaeologists and continue to the present day (Figure 4-15).[192] Although we have learnt much about the statue and sanctuary, the most significant effect of the excavations may have been the creation of the modern Olympic Games in 1896.

The Afterlife of the Statue

As for the wondrous statue, its influence may still be with us. The statue was in Constantinople for over one hundred years before it was destroyed by fire in 462 CE, and during that time the city became the eastern centre of Christianity. The great statue of Zeus may

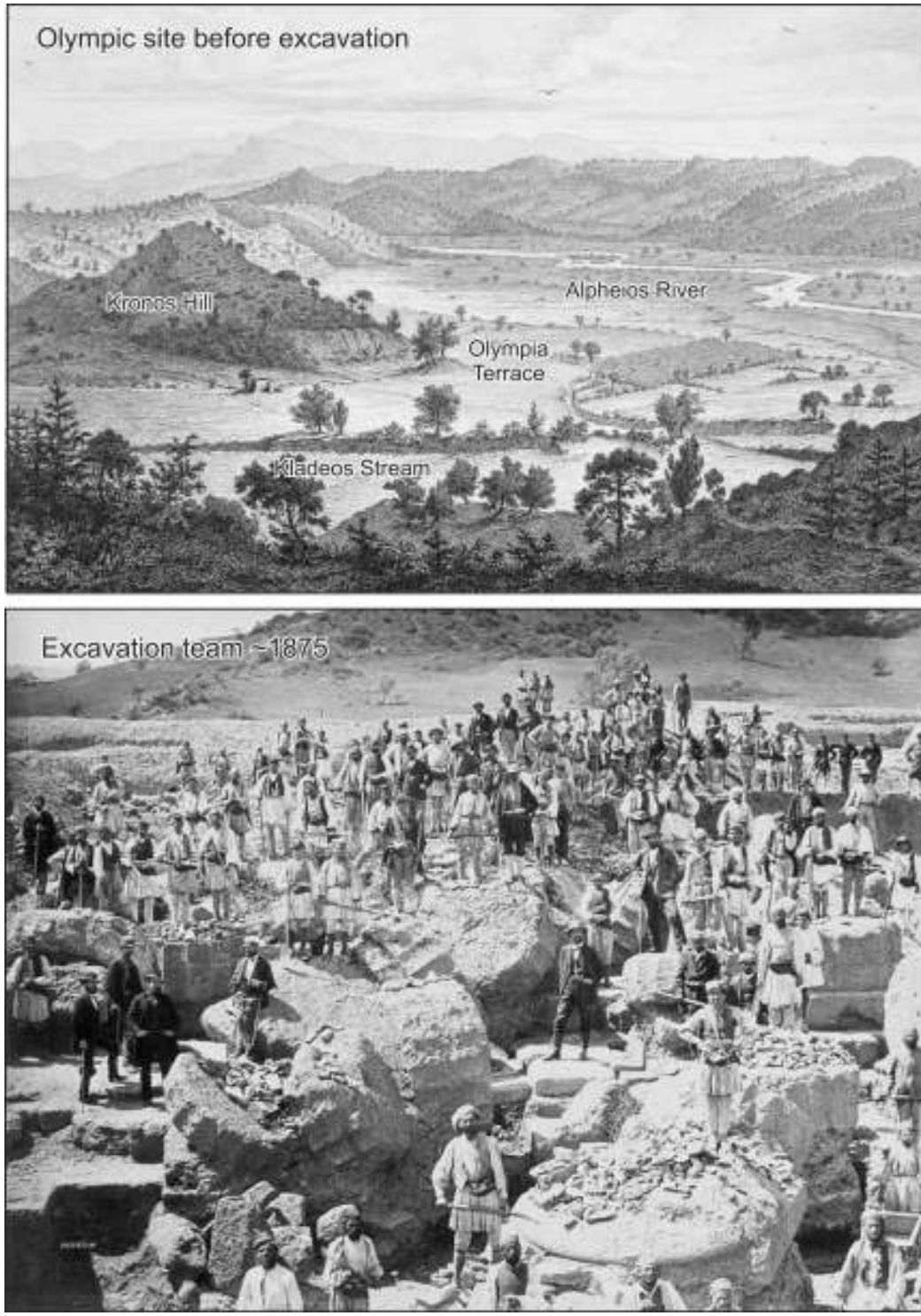


Figure 4-15: The site was almost deserted in 1875 before the excavations started. Subsequent excavation involved a huge team, here mostly dressed in traditional kilts. Boetticher, A., 1886, *Olympia, das Fest und seine Stätte*. Verlag von Julius Springer, Berlin; Curtius, E., G. Hirschfeld, and F. Adler, 1876, *Die Ausgrabungen zu Olympia*. XXII Tafeln in Lichtdruckt Band 1, Verlag von Ernst Wasmuth: Berlin.

Figure 4-16: The statue of Zeus at Olympia may have inspired the canonical image of Jesus Christ, seen here in a mosaic from the sixth century church of Ayia Sophia (*Holy Wisdom*) in Istanbul. Photo © Edal Anton Lefterov, Wikimedia Commons, CC BY-SA 3.0.

have inspired the familiar image of Christ Pantocrator (*Almighty*) as a young, powerful man with long hair and a full beard (Figure 4-16).

Pheidias's Zeus has never been reproduced but in Nashville, Tennessee, USA, there is a recreation of his Athena in a full-size replica of the Parthenon. Looking at it, we can easily imagine the impression produced by these huge gold and ivory creations, set up in

confined spaces (Plate 10a). The Nashville Athena may seem gaudy to modern taste but the original statue was never intended to be seen in bright light. To get the feeling of the ancient Zeus, perhaps we should go further afield, to Nara, Japan, to see the 15-metre-high gilt bronze Buddha housed in the wooden Tōdai-ji Temple. This statue almost fills the whole space, its power magnified by the gloomy light coming in from the doors, as I imagine the wondrous recreation of Zeus to have been illuminated for those who were permitted to see it.

5

The Mausoleum at Halicarnassus

The Mausoleum

The Mausoleum was a vast tomb built to house the earthly remains of Mausolus, a 4th century BCE ruler of the Persian province of Caria (Figure 5-1, Figure 5-2). At 45 metres high, it was the largest mortuary monument in the Mediterranean region, except for the Pyramids of Giza, and also excelled from all others in the quality and quantity of its statuary. It was the pride of the Carians and was renowned throughout the Western World until its collapse in the 14th century. Now, all that is left is a hole in the ground, some sculptural fragments, and the memory of its past glory.

There are many ancient descriptions of the monument, but the most detailed account was written by Pliny the Elder in 77–79 CE: "Scopas had for rivals and contemporaries, Bryaxis, Timotheus, and Leochares, artists whom we are bound to mention together, from the fact that they worked together at the Mausoleum; such being the name of the tomb that was erected by his wife Artemisia in honour of Mausolus, a petty king of Caria, who died in the second year of the 107th Olympiad. It was through the exertions of these artists more particularly, that this work came to be reckoned one of the Seven Wonders of the World. The circumference of this building is 440 feet [140 metres] and the two sides are narrower than the front and back

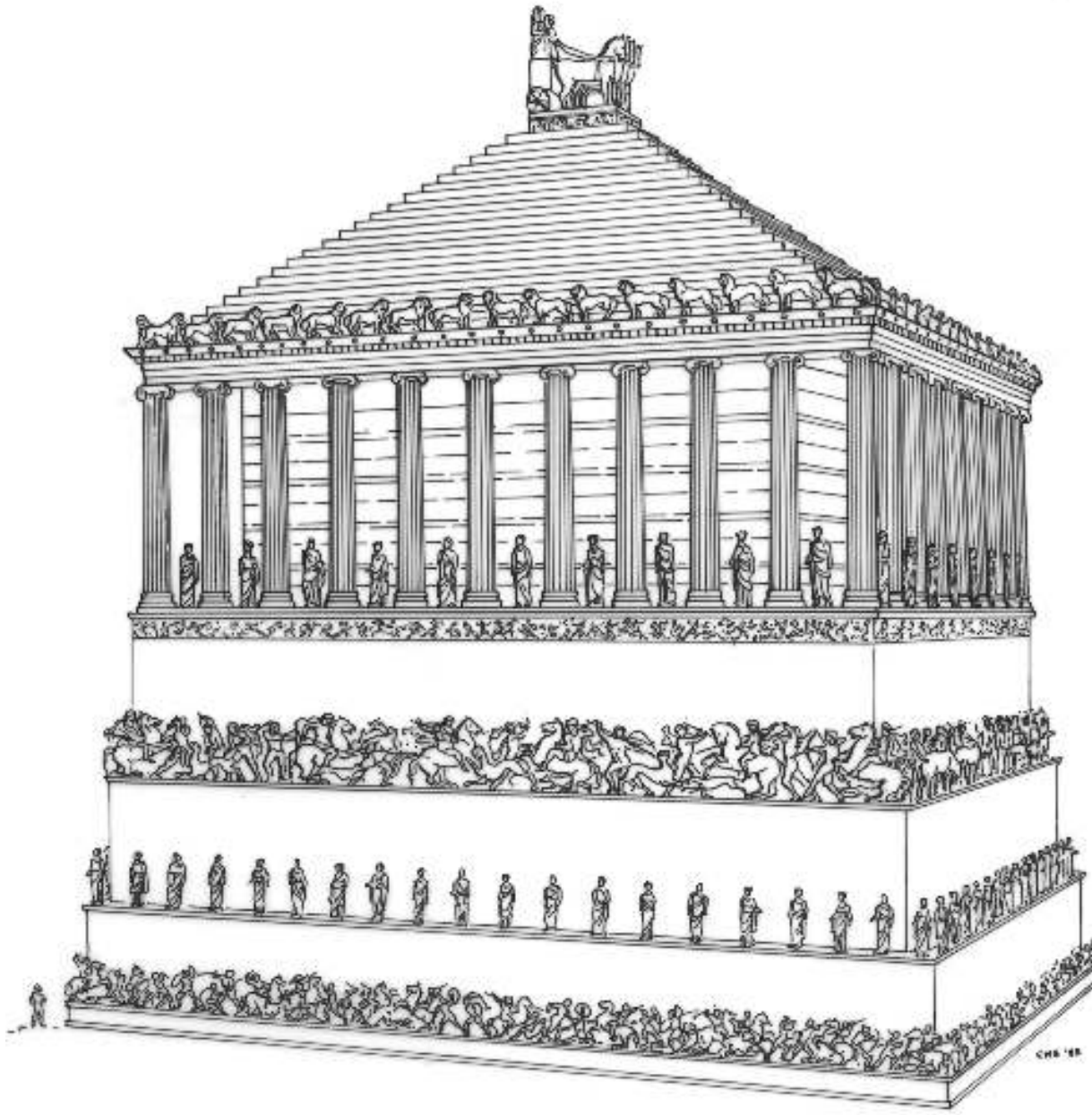


Figure 5-1: The original Mausoleum was the monumental tomb of King Mausolus at Halicarnassus, completed in 340 BCE. It was famous for its size and rich marble sculptures, which only now survive as fragments. This is one of many visual reconstructions as almost nothing remains of the building. Image © Andrew Stewart and Candace Smith.

[~38 × ~32 m]. The colonnade is 25 cubits high [11 m], and has 36 columns . . . The east side was sculptured by Scopas, the north by Bryaxis, the south by Timotheus, and the west by Leochares; but, before their task was completed, Queen Artemisia died. They did not

leave their work, however, until it was finished, considering that it was at once a memorial of their own fame and the sculptor's art: and, to this day even, it is undecided which of them has excelled. A fifth artist also took part in the work; for above the row of columns there is a pyramid erected, equal in height to the building below, and formed of 24 steps, which gradually taper upwards towards the summit, where a platform is crowned with a representation of a four-horse chariot by Pythius. This addition makes the total height of the work 141 feet [45 m]." (*Pliny the Elder*, Natural History, Book 36:30–31.)

Although many were impressed by the Mausoleum, not all ancient writers were so enthusiastic—I've already mentioned Lucian's satirical comments on the statue of Zeus and he had similar things to say about Mausolus and his tomb (see box 5-1: A Conversation in Hades).

Caria was a small kingdom of Indigenous people on the western edge of Anatolia. Although the Carians had their own language, they were greatly influenced by the culture of the neighbouring Greek cities, even after they were conquered by the Persians in 545 BCE.

The story of the Mausoleum starts in 387 BCE when peace was finally made between the Athenians, Spartans, and Persians.[198] Ten years later, Mausolus came to the throne of Caria and sought to exploit this period of stability and prosperity. The inland capital that he inherited at Mylasa (now Milas) was not suitable for the development of maritime trade, so he moved his capital to Halicarnassus (now Bodrum) to take advantage of the fine natural harbour (Figure 5-2, Figure 5-3). The settlement was already old, with remains dating from 1400 BCE, and well known as the hometown of historian Herodotus, born a hundred years before Mausolus. However, it just consisted of several villages before Mausolus started his work.

In 377 BCE, Mausolus ordered the rebuilding of Halicarnassus on a huge scale. The new city was surrounded by massive limestone walls, pierced by two monumental gates.[201–202] To the west and north of the city, the walls were mostly built on solid rock and were reinforced with forts. However, the section of the wall in the southeast was built on alluvium (loose sand and gravel) washed out of the hills and hence was

Box 5-1 A Conversation in Hades

Lucian of Samosata imagined a conversation in Hades between the souls of Diogenes of Sinope, the philosopher who was supposed to have lived in a barrel, and Mausolus, King of Caria:

Diogenes. Why so proud, Carian? How are you better than the rest of us?

Mausolus. Sinopean, to begin with, I was a king; The king of all Caria, ruler of many Lydians, subduer of islands, conqueror of well-nigh the whole of Ionia, even to the borders of Miletus. Further, I was comely, and of noble stature, and a mighty warrior. Finally, a vast tomb lies over me in Halicarnassus, of such dimensions, of such exquisite beauty as no other soul can boast. Thereon are the perfect semblances of man and horse, carved in the fairest marble; scarcely may a temple be found to match it. These are the grounds of my pride: are they inadequate?

Diogenes. Kingship, beauty, heavy tomb—is that it?

Mausolus. It is as you say.

Diogenes. But, my handsome Mausolus, the power and the beauty are no longer there. If we were to appoint an umpire now on the question of comeliness, I see no reason why he should prefer your skull to mine. Both are bald and bare of flesh; our teeth are equally in evidence; each of us has lost his eyes, and each is snub-nosed. Then as to the tomb and the costly marbles, I dare say such a fine building gives the Halicarnassians something to brag about and show off to strangers: but I don't see, friend, that you are the better for it unless it is that you claim to carry more weight than the rest of us, with all that marble on the top of you.

Mausolus. Then all is to go for nothing? Mausolus and Diogenes are to rank as equals?

Diogenes. Equals! My dear sir, no—I don't say that. While Mausolus is groaning over the memories of earth, and the felicity which he supposed to be his, Diogenes will be chuckling. While Mausolus boasts of the tomb raised to him

by Artemisia, his wife and sister, Diogenes knows not whether he has a tomb or no—the question never having occurred to him; he knows only that his name is on the tongues of the wise, as one who lived the life of a man; a higher monument than yours, vile Carian slave, and set on firmer foundations.

"Dialogues of the Dead."[224]

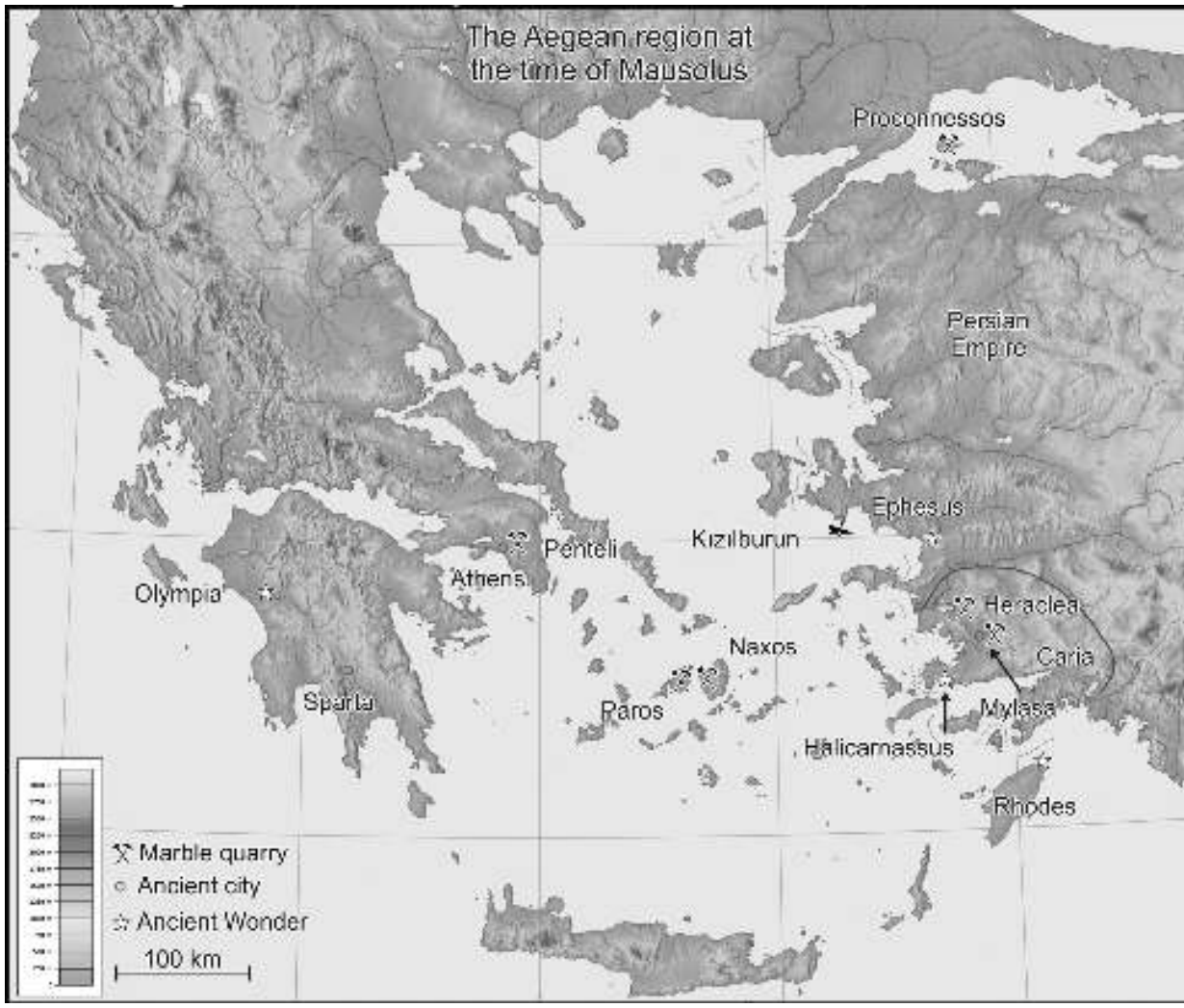


Figure 5-2: The Mausoleum was in Halicarnassus (now Bodrum, Turkey), the capital of the Persian province of Caria. It was constructed using marble from many places in the Persian Empire and the Aegean region. Map by the author.

easily undermined. A rectangular grid of streets was laid out to fill the hollow above the harbour (Figure 5-3). Houses were built by the inhabitants of the former villages as well as people forcibly displaced from settlements along the coast to the west. Mausolus's palace was constructed on an island southeast of the harbour, but the city's focus was his tomb on the main street (Figure 5-3). The Mausoleum was erected on the southern slopes of a low hill (now Göktepe Hill) overlooking the harbour and must have towered above the city, making it easily visible from the sea. Mausolus started construction of his tomb and its sanctuary but died in 353 BCE before they could be completed. Artemisia, his widow and sister, continued the project until 351 BCE when she died. It was probably finished by his brother Idreus and his wife/sister Ada in about 340 BCE, just before the arrival of a powerful army.

In 334 BCE, Alexander the Great left Macedonia to continue the conflict with the Persians started by his father Phillip II. After an important victory at Granicus in northwestern Turkey, he arrived at Halicarnassus and put his camp to the southeast where he had access to the sea and where the walls were weakest. The advantage went from defenders to attackers several times but finally Alexander was able to get a siege engine in place and break down the walls. When the defenders saw that all was lost, they set fire to the city but fortuitously the Mausoleum was not damaged. It survived until mediaeval times when it was brought down by an earthquake, which I'll talk about later.

Visual reconstructions of the Mausoleum are based on ancient descriptions, such as that of Pliny, as well as excavation reports and sculptures recycled in later buildings (Plate 10b). To these, we can add a 2nd century BCE tomb at Milas that is thought to be a small-scale copy of the Mausoleum. Many different models have been proposed but the overall plan is clear:[203] unlike most sacred buildings, the Mausoleum was solid, except for the actual burial chamber that lay at the base, mostly below ground level, in this way resembling the Giza Pyramids (Figure 5-1, Figure 5-6). The overall style reflects both Greek and Asiatic influences on the Indigenous Carian culture (Figure 5-4).[205]

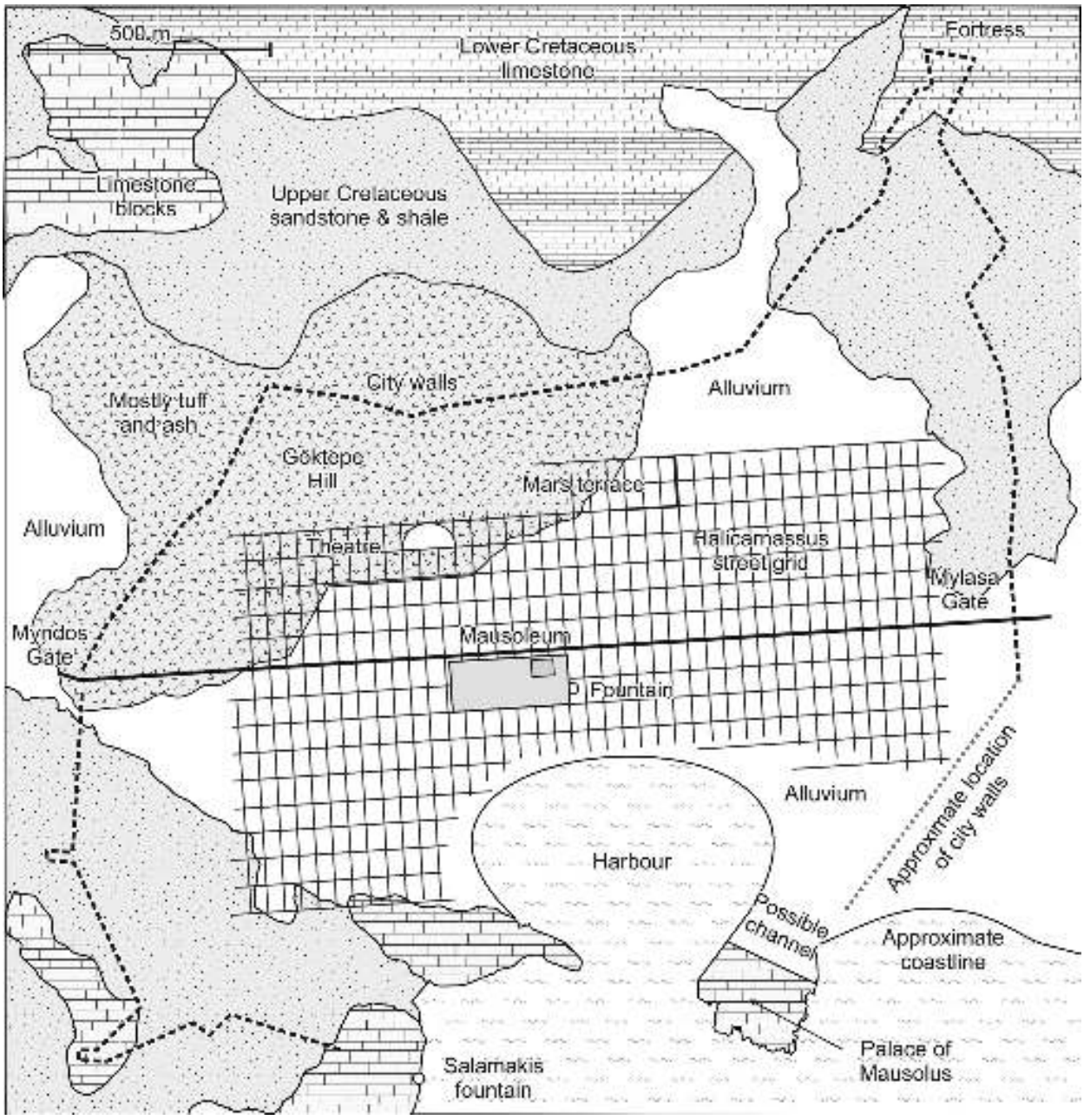


Figure 5-3: Halicarnassus lay in a basin lined with alluvial sediments (alluvium), surrounded by hills of hard limestone, soft sandstones, and young volcanic ash. The Mausoleum stood on the main street in the centre of the city. The Palace of Mausolus was on an island, now a peninsula covered by the Knights' Castle. Map by author after Bernoulli, D., P.C. De Graciansky, and O. Monod, 1974, "The Extension of the Lycian Nappes (SW Turkey) into the Southeastern Aegean Islands," *Eclogae Geologicae Helvetiae*, 67(1): 39–90; Masse, J.-P. et al., 2015, "Berriasian rudist faunas and micropalaeontology of Stramberk type carbonate exotics from the Lycian nappes, Bodrum Peninsula, southwest Turkey." *Cretaceous Research* 56: 76-92.

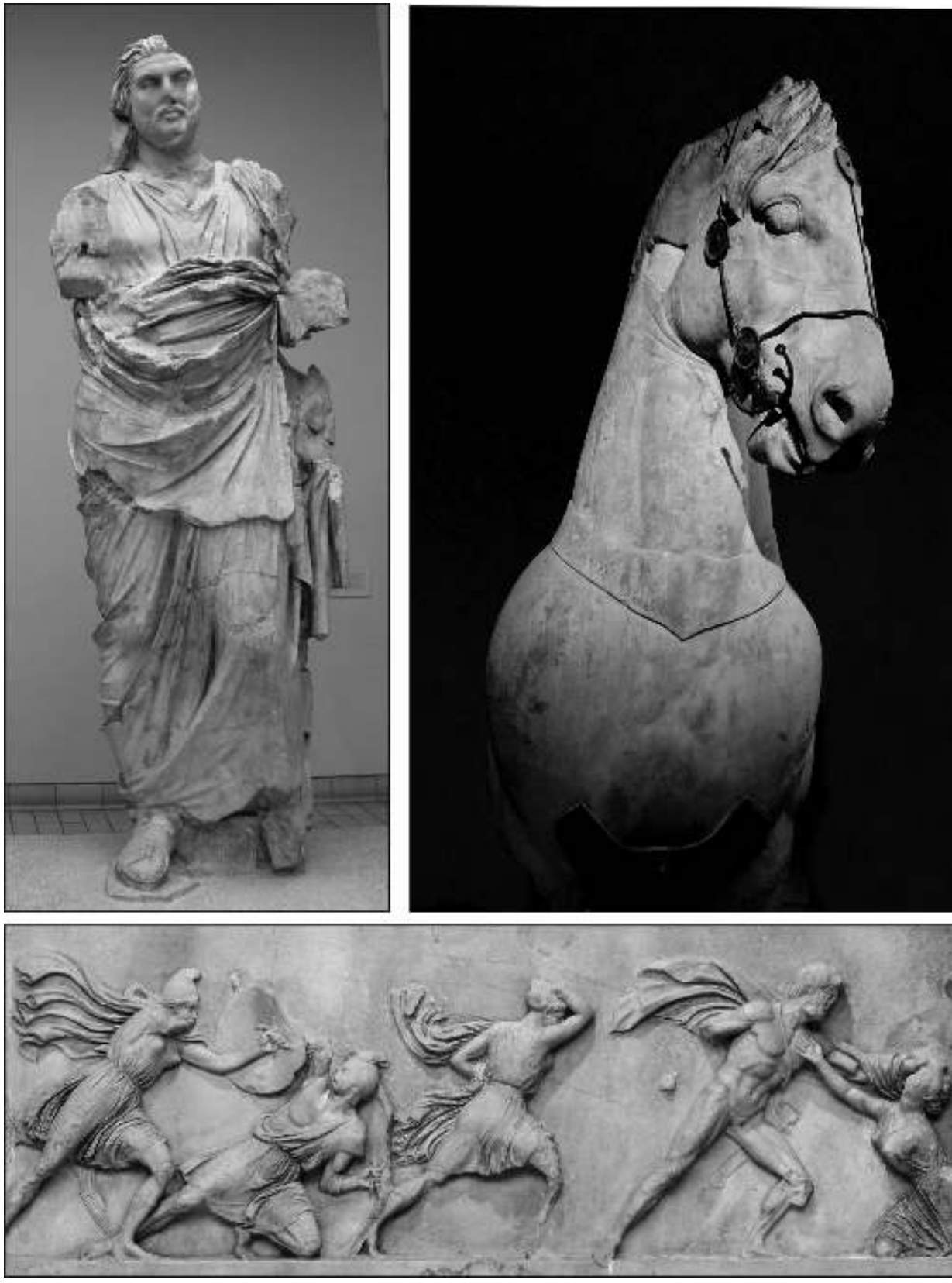


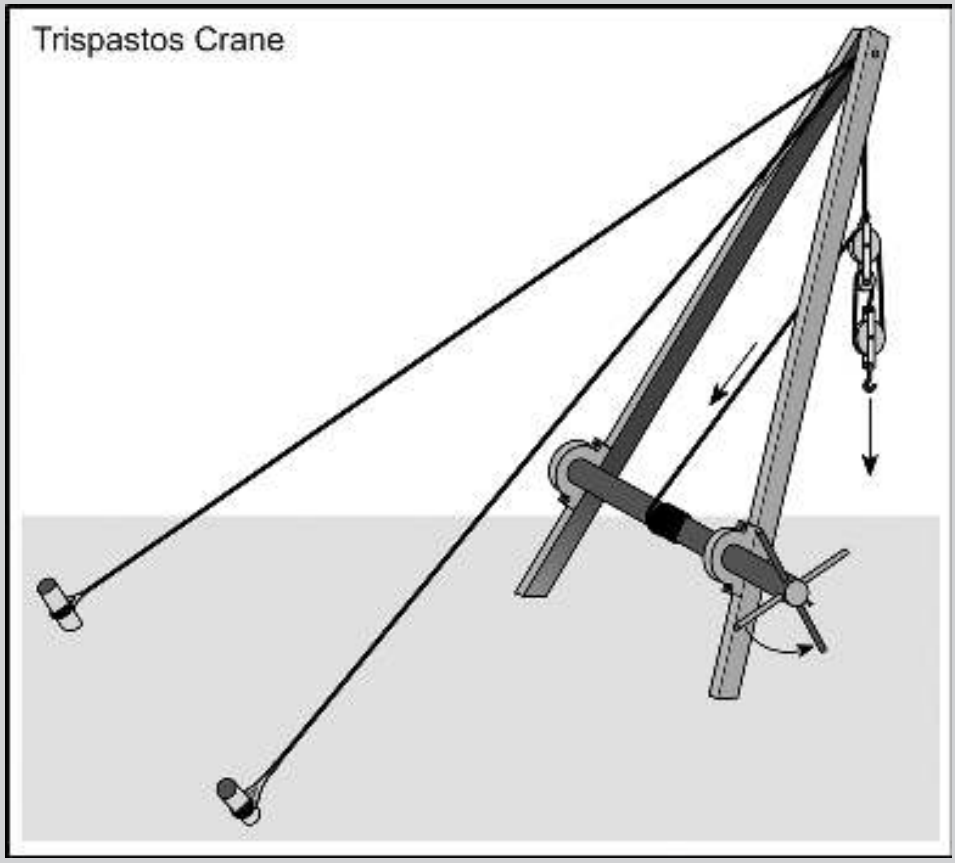
Figure 5-4: The Mausoleum was richly decorated with marble sculptures. A three-metre-high statue of Mausolus, or one of his ancestors, stood between the columns in the upper part of the monument. Four life-sized horses harnessed to a chariot stood on the top of the roof. The core of the building was wrapped with friezes of mythological scenes painted in bright colours: here Greeks are fighting Amazons. Photos © Carole Raddato / Wikimedia Commons / CC-BY 2.0/; © Jastrow / Wikimedia Commons Public Domain; © Marie-Lan Nguyen / Wikimedia Commons / CC-BY 2.5.

The foundations and core were made of a distinctive green rock of local volcanic origin. Many blocks of this rock can still be seen at the site of the Mausoleum and in the walls of the Knight's castle—it is estimated that 160,000 were used, each 90 × 90 × 30 centimetres. They were lifted into place using cranes, trimmed and then secured to the neighbouring blocks using iron clamps set in molten lead (see box 5-2: Lifting Stone Blocks). This tuff is a strong rock that was easy to exploit and cut but with clear shortcomings: it could not be polished and it weathered easily, which is one reason why it was concealed beneath a shell of marble, regarded as a more prestigious and attractive material.

Almost all the visible parts of the Mausoleum were made of white from several different sources in both Persia and Greece (Figure 5-4, Figure 5-5).[204,205] The choice seems to have been based on the cost, availability, and properties of the marble, and not the personal taste of the sculptors. One of the most important was Proconnessos marble from Marmora Island, a source so important that the surrounding sea was named after it (Figure 5-2).[206] This marble was available in large blocks and was relatively cheap, certainly later on when Roman documents gave actual prices,[207] but was coarse-grained and commonly streaked with grey. Proconnessos marble was complemented by coarse-grained white marble from nearby quarries at Mylasa, the former capital; and Heraclea further north, accessible at that time by sea before the Maeander Valley silted up.

The free-standing statues were carved from a finer-grained, white marble quarried at Mt. Penteli, just to the east of Athens (Figure 5-4). This was the same marble that was used for the Parthenon, finished a hundred years earlier, and the link may have been deliberate. The heads of several statues were carved from Lychnites marble from Paros. This fine-grained, translucent marble was expensive, as it was quarried underground, and generally available only in small blocks. It was used for the exposed parts of composite statues as it could be highly polished to resemble pale skin. Where possible, marble was transported by sea—clearly a treacherous undertaking as over sixty

Box 5-2 Lifting Stone Blocks



A crane used for raising blocks. Image by author after © Sting / Wikimedia Commons, CC BY-SA 4.0.

People have needed to raise stone blocks ever since the first monuments were conceived. In Old Kingdom Egypt and Archaic Greece, blocks appear to have been dragged up ramps by large teams of men, although levers may have been used to the final stages of construction (see Chapter 2). Building methods started to change in early 6th century BCE, when we first see holes and cuttings in some blocks, showing that lifting tongs and ropes must have been used to lift them into position.[225,226] We don't know much about the cranes used at this time but they may have resembled those used in Roman times and consisted of a wooden A-frame with a winch and pulley. The crane's capacity could have been increased by the use of compound pulleys, which were described by Aristotle in the 4th century BCE. The Romans further increased the maximum lift by replacing the winch with a treadwheel powered by slaves.

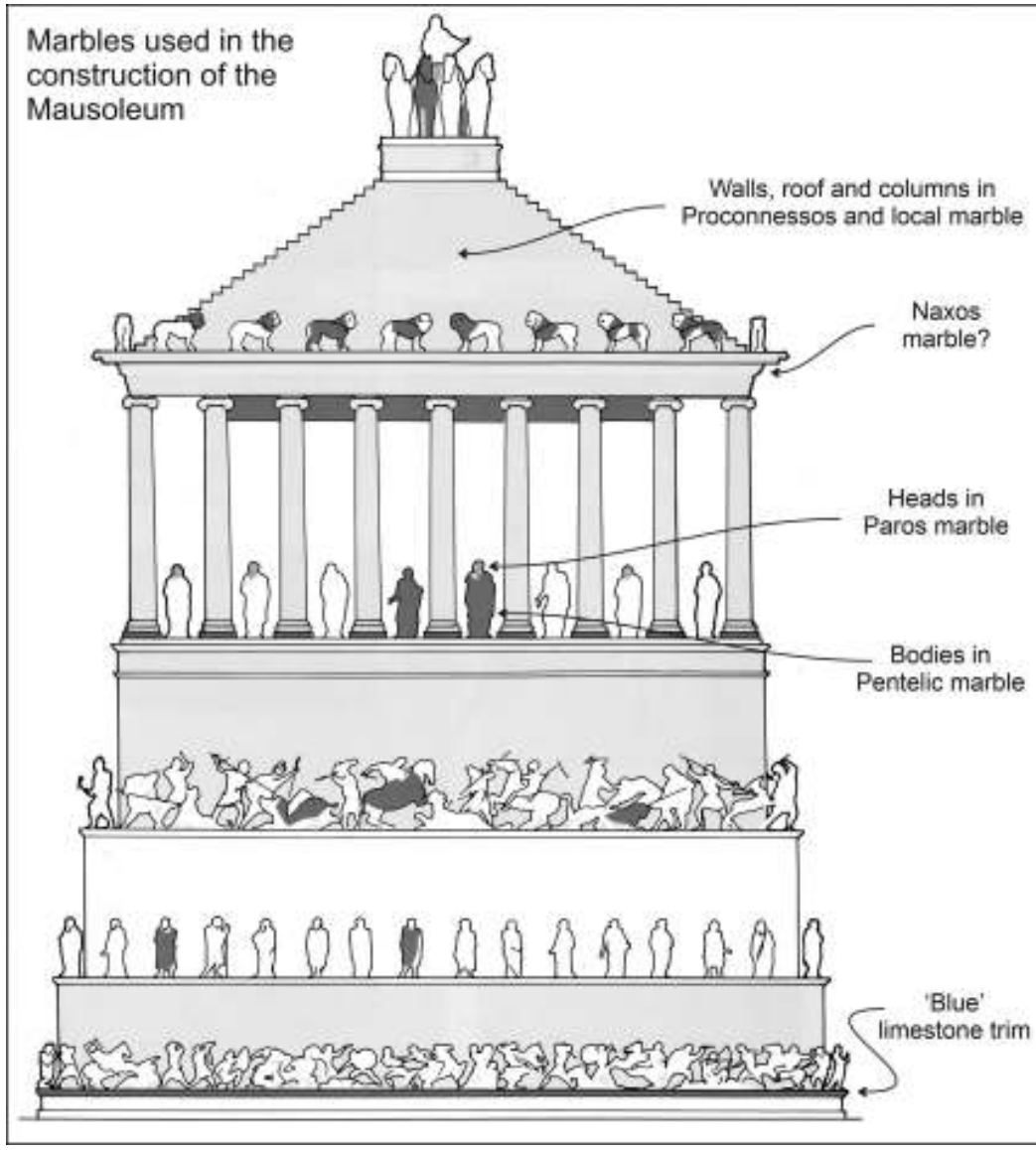

Marbles used in the construction of the Mausoleum
Walls, roof and columns in Proconnessos and local marble
Naxos marble?
Heads in Paros marble
Bodies in Pentelic marble
'Blue' limestone trim

Figure 5-5: The Mausoleum, built around a core of volcanic rock, was covered with sculptures and blocks of many different types of marble and limestone. In this image, the different rocks have been colour coded—they are not the actual colours that were used on the finished building. Image by author after Walker, S. and K.J. Matthews, 1997, "The Marbles of the Mausoleum," in Sculptors and Sculpture of Caria and the Dodecanese, I. Jenkins and G.B. Waywell, editors, British Museum Press, London. 49-59; Waywell, G.B., 1978, The free-standing sculptures of the Mausoleum at Halicarnassus in the British Museum. British Museum Publications, London.

Box 5-3 An Ancient Marble-Carrying Ship

Excavation of the Kızılburun wreck. Image by author after Carlson, D.N., 2016, The Underwater Recovery of Monumental Marble Column Drums from an Ancient Shipwreck at Kızılburun, Turkey. *Journal of Maritime Archaeology* 11(2): 219–230.

The boat wrecked at Kızılburun (*Cape Crimson*) about two thousand years ago was 15–20 metres long, 4.5-5 metres wide, and carried a load of 50 tons of marble. It included eight column-drums and a capital, enough to make a single Doric column ten metres high, as well as sacred Louteria basins and grave markers.[227] The marble was from the Proconnessos quarries on Marmara Island, in the Sea of Marmara 400 kilometres to the north, and was destined for Claros, 15 kilometres northeast of Ephesus. Although it sank three hundred years after the Mausoleum was completed, some of the marble used in the Mausoleum was from the same quarries and would have been transported in the same way.

wrecks with marble blocks have been found, mostly dating from the Roman period[208] (see box 5-3: An Ancient Marble-Carrying Ship).

A minor, but architecturally important material, was a red-veined grey limestone, commonly called "blue limestone," which used for the base of columns and some of the statues, to provide a visual contrast with the white marble. It probably came from quarries in the hills to the north of Halicarnassus.

The common conception of ancient statues and temples is of austere pale marble or limestone, but this is far from the truth, as surface treatments and coloured paints were used extensively. When the Mausoleum was first excavated in 1856, coloured paint was still evident on decorative blocks, sculptures, and friezes (Plate 11a), but most of it flaked off as the blocks dried out and were rubbed during transportation. Traces of pigments show that sculptures and figures in the friezes were highlighted in red paint and yellowish varnish, and the backgrounds were painted blue.[209,210] Parts of some sculptures and friezes may also have been covered with thin sheets of gold. Finally, parts of the horses on the roof were covered with a thin layer of lead.

The Mausoleum was surrounded by a huge unpaved courtyard 242 × 105 metres—equal in area to five football fields—walled on all sides with a gate to the east (Figure 5-6). The walls' lower parts were made of limestone but the upper 2.5 metres were white marble. Construction started with Proconnessos marble and was completed with marble from other sources such as Mylasa and Heraclea.[204] The wall was accented by blocks of a striking pinkish porphyry, containing white feldspar crystals up to 3 centimetres long (Plate 11b). We do not know if the courtyard was intended to be empty, its sole function being to offset the tomb's glory; or if it housed a garden in the Persian style, perhaps like the royal gardens of Babylon or Nineveh; or even if was intended to be a necropolis for the tombs of Mausolus's successors. It was as big as the stadium at Olympia and could have been planned to host commemorative games.

Another feature of the Mausoleum complex was a water fountain built into the eastern supporting wall of the courtyard, fed by an aqueduct that tapped a water source somewhere to the northwest (Figure 5-6).[198] We know that this aqueduct predated the Mausoleum as it had to be diverted around the monument. If the original spring was regarded as sacred, like many in this region, then it may have guided the selection of the site for the Mausoleum, as well as providing a useful resource for the citizens of Halicarnassus.

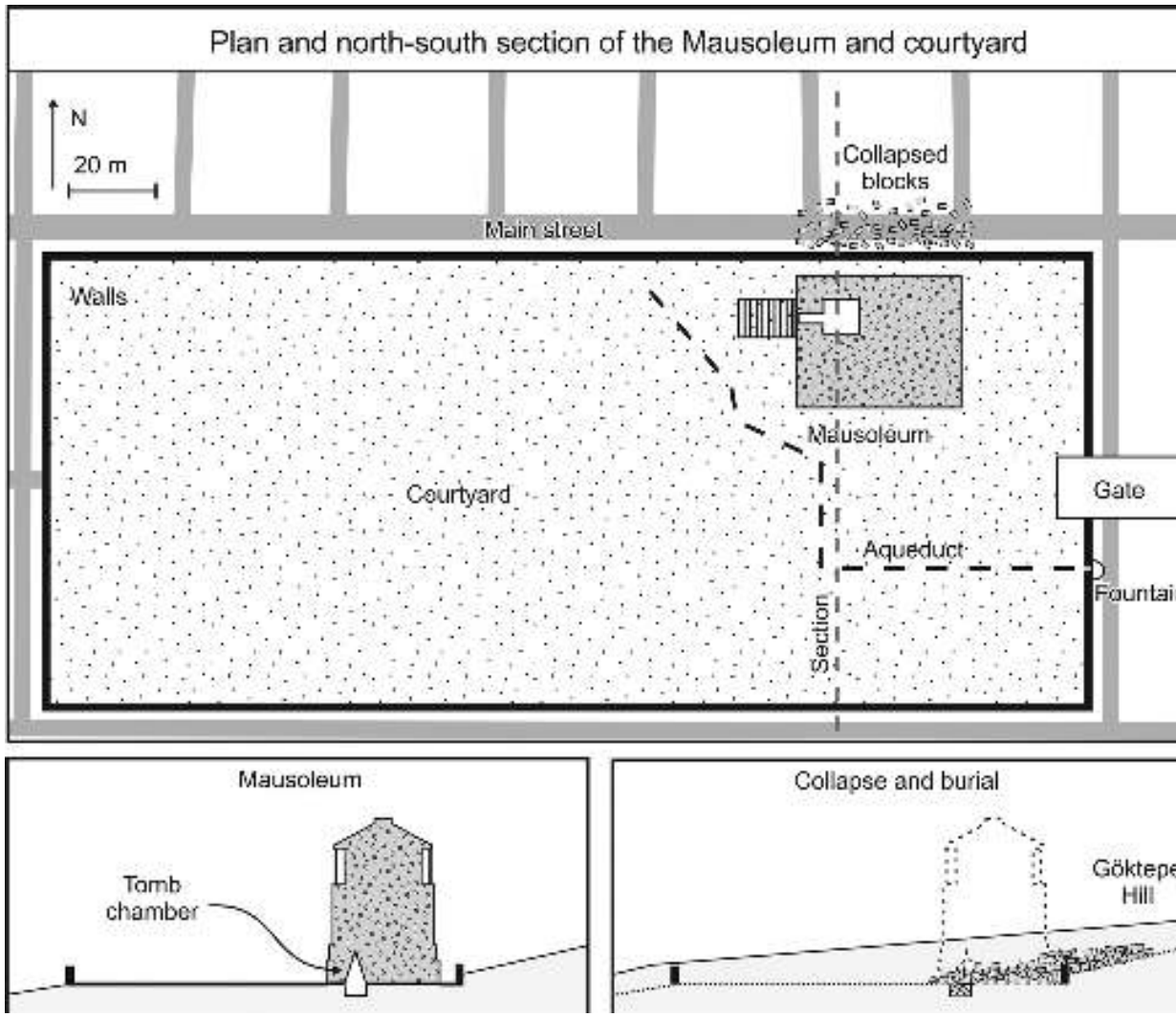


Figure 5-6: The Mausoleum was set in a courtyard, surrounded by walls of limestone, marble and porphyry, accessible by a monumental gate. An aqueduct ran under the courtyard to emerge at a fountain in the wall. After the Mausoleum's collapse, blocks and sculptures were soon buried under soil washed down from Göktepe Hill to the north and thus preserved from pillaging. Image by author after Pedersen, P., 2013, "The 4th century BC 'Ionian Renaissance' and Karian identity." *Publications de l'Institut Français d'Études Anatoliennes* 28(1): 33–64; Jeppesen, K. and I. Zahle, 1973, "The Site of the Mausoleum at Halicarnassus Reexcavated." *American Journal of Archaeology* 77(3): 336–338.

Mausolus was buried in a chamber cut into the bedrock under the Mausoleum, which was accessed by steps from the west, and sealed by large blocks after the funeral ceremony. His wife, Artemisia, was buried in the antechamber. Both were probably cremated and their remains placed in an urn, rather than a sarcophagus. The burial was looted, probably quite soon after completion of the Mausoleum, by

robbers who tunnelled through the soft volcanic ash underlying the building, bypassing the sealing blocks. The burial was probably opulent, but all that remained when excavated by archaeologists were eggshells, animal bones, and a few fragments of glass, gold, and semi-precious stones [211].

The construction of the Palace, the Mausoleum, and the city walls all needed vast resources of stone. The question is where did all this material come from and how was it formed?

Building and Sculptural Stone

The walls of the city were made of hard grey limestone, which was also used for decorative elements in the Mausoleum and probably for domestic buildings in the city as well. These rocks are the oldest on the Bodrum peninsula and are resistant to erosion, which is why they make up the backbone of the peninsula, including its highest peak, Mt. Pazar (Figure 5-7). The limestones were formed on a shallow platform in tropical seas, like the modern Bahamas, when this region was further south two hundred to one hundred million years ago (Jurassic-Upper Cretaceous).[199–200] About eighty-five million years ago, huge blocks of this platform broke off and slid down into deeper water where mud and sand were accumulating. The peninsulas on either side of the harbour are such blocks of this hard limestone and were important for the development of the city (Figure 5-3, Figure 5-8).[200]

The core of the Mausoleum was built of volcanic rocks that erupted about eleven million years ago through the limestones of the peninsula.[212] This volcano was one of many in a broad swath that extended northwards along the edge of the Aegean Sea and volcanism was partly caused by the north-south crustal stretching in western Turkey and the Aegean region that is mentioned in Chapter 6.

The Bodrum volcano did not resemble the classic steep-sided cones of Mt. Vesuvius or Fuji but instead was broad and low, with a

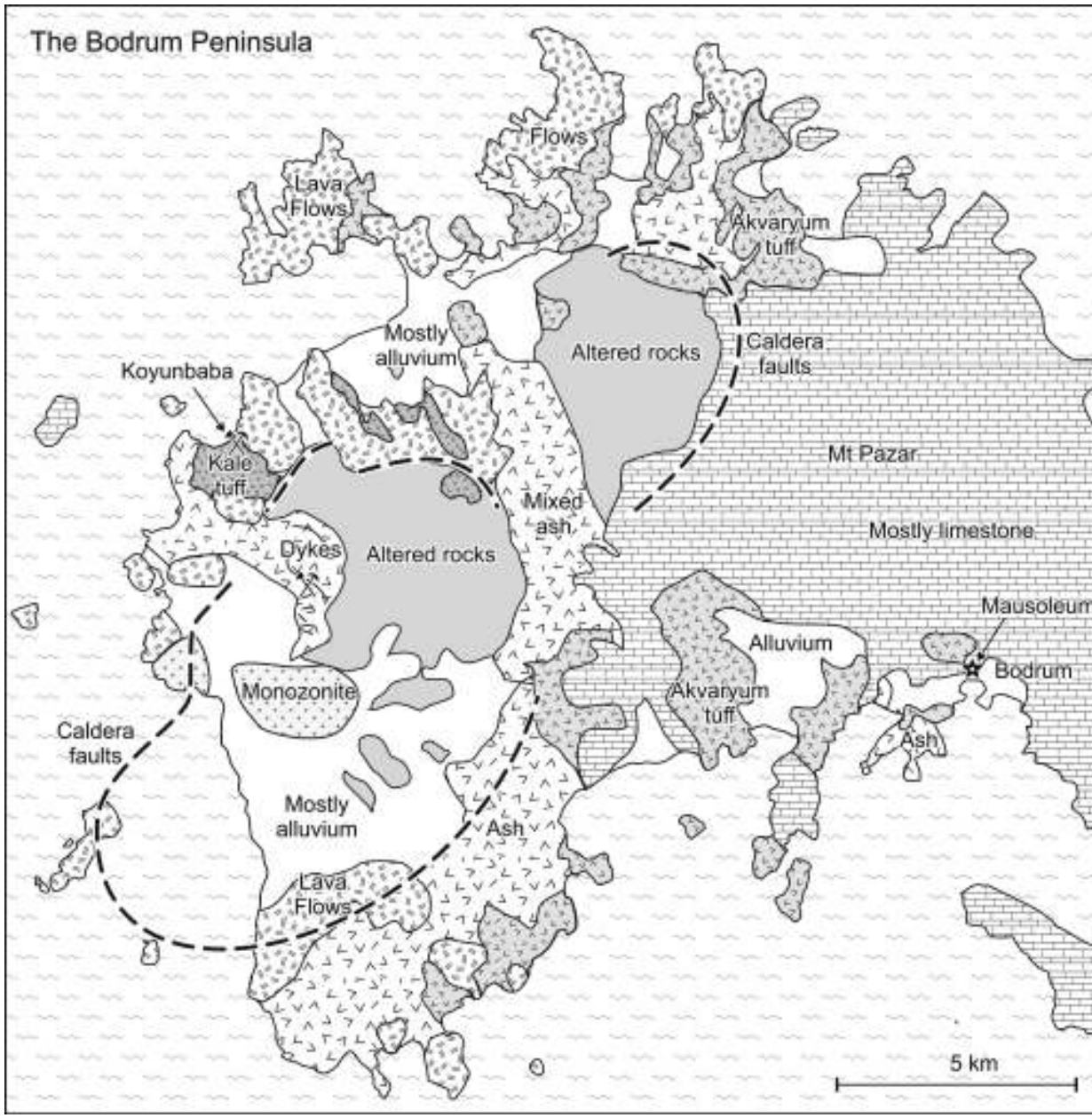


Figure 5-7: Halicarnassus (modern Bodrum) lay on the south coast of a peninsula mostly underlain by a hard limestone that has resisted erosion. A huge volcano formed about eleven million years ago on top of the limestone. The two largest eruptions came out along the caldera faults and created deposits of the Kale tuff, which was quarried to make the core of the Mausoleum, and the Akvaryum tuff that underlies its foundations. Map by author after Ulusoy, I. et al., 2004, Volcanic'' and Deformation History of the Bodrum Resurgent Caldera System (Southwestern Turkey).'' *Journal of Volcanology and Geothermal Research* 136: 71–96; Higgins, M.D. and R. Higgins, 1996, *A Geological Companion to Greece and the Aegean*. Cornell University Press / Duckworth Publishers: Ithaca, NY / London.

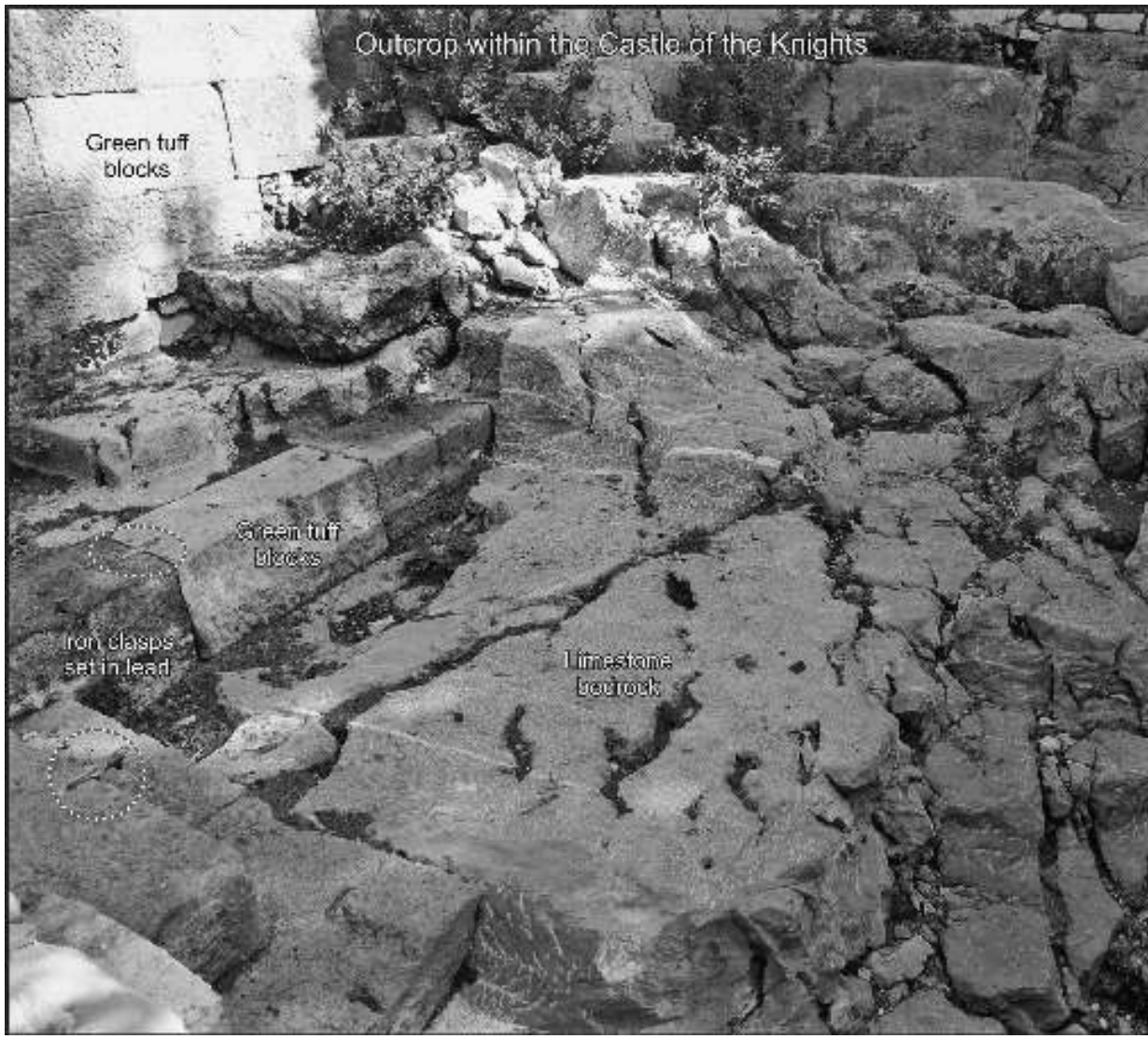


Figure 5-8: The walls of Mausolus's Palace were made of green tuff and limestone blocks, held together with iron clasps to stabilise the structure against earthquakes. The limestone bedrock was carved out to accommodate the blocks, further increasing the strength of the walls. Photo courtesy of the author.

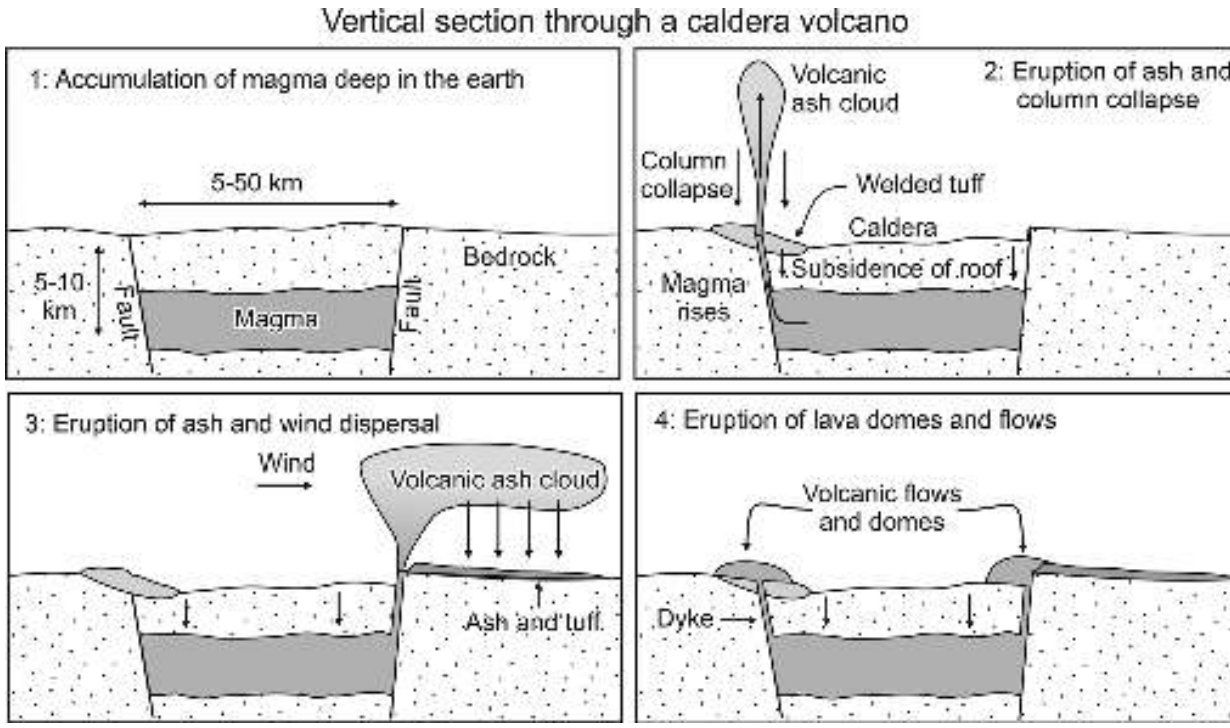


Figure 5-9: Caldera volcanoes, such as that on the Bodrum Peninsula, mostly erupt volcanic ash, which can be dispersed far from the volcanic vent, commonly followed by lava flows and domes. Image by the author.

depression at the centre. Rather than producing flows of viscous lava, it mostly erupted ash and pumice that was moved away from the vent by hot avalanches or wind. Such volcanoes are quite common and their eruptions can be huge—there are good examples at Milos Island and the older ash eruptions of Thera (Santorini), including the spectacular "Minoan" eruption of ~1600 BCE.

The eruptive cycle of such a volcano starts with the accumulation of magma in the crust (Figure 5-9).[212] The volume of magma increases until it became so large that the roof founders along elliptical faults, making a cooking-pan shaped depression called a caldera. As the eruption proceeds, magma rises towards the surface and the pressure is reduced, which makes water dissolved in the molten rock boil. The magma is initially transformed into a bubbly foam, which can solidify to make pumice, or expansion can also continue until the bubbles joined together, creating a hot mixture of pumice, ash, and gas that erupts as a jet from the volcanic vent. This mixture is lighter than

the atmosphere so rises buoyantly making an immense column of ash tens of kilometres high. If the force of the eruption wanes, then the column may collapse and make hot ash flows that spread out in all directions. Such ash may be so hot that it welds itself together to make a relatively durable rock called tuff (not to be confused with *tufa*, which is a type of limestone formed at mineral springs). In other eruptions, high-altitude winds can disperse the ash, which cools and falls back to the earth to form deposits of looser material.

Many eruptions from Bodrum volcano covered the western part of the peninsula with up to 500 metres of ash, tuff, and lava, with two particularly important ones produced by caldera collapse (Figure 5-7, Figure 5-9). The small Kale (*Castle*) tuff was deposited to the northeast of the caldera and the larger Akvaryum tuff and ash fell to the east, as far as Göktepe Hill. The greenish Kale tuff is full of fragments of volcanic material and blocks of the bedrock through which it erupted. It is resistant to erosion and easy to cut using simple tools, and hence made good construction material. It was quarried near Koyunbaba to extract blocks for the core of the Mausoleum and the walls of the Palace (Plate 11b).[213] We encounter the Akvaryum ash and tuff in the rock-cut tombs of Göktepe Hill and the foundations of the Mausoleum.

After the caldera's collapse, the volcanism became less violent but there were still numerous small eruptions of lava, some of which came up the old caldera faults (Figure 5-9). During one of the last events, magma was squeezed up into cracks to solidify as dykes—so-called because they resist erosion and stand up like walls. Those seen 3 kilometres southeast of the Koyunbaba quarries may well have been the source of the striking pinkish porphyry used for decorating the walls of the Mausoleum (Figure 5-7).[212]

Although the core of the Mausoleum was made of volcanic rocks, what the ancient visitors saw and admired were its exterior walls and sculpture, which were all made of white or pale grey marble (Figure 5-4; see Chapter 6—Marble for the Temple). Such rocks were quarried throughout the region (Figure 5-2), and it is not always easy to

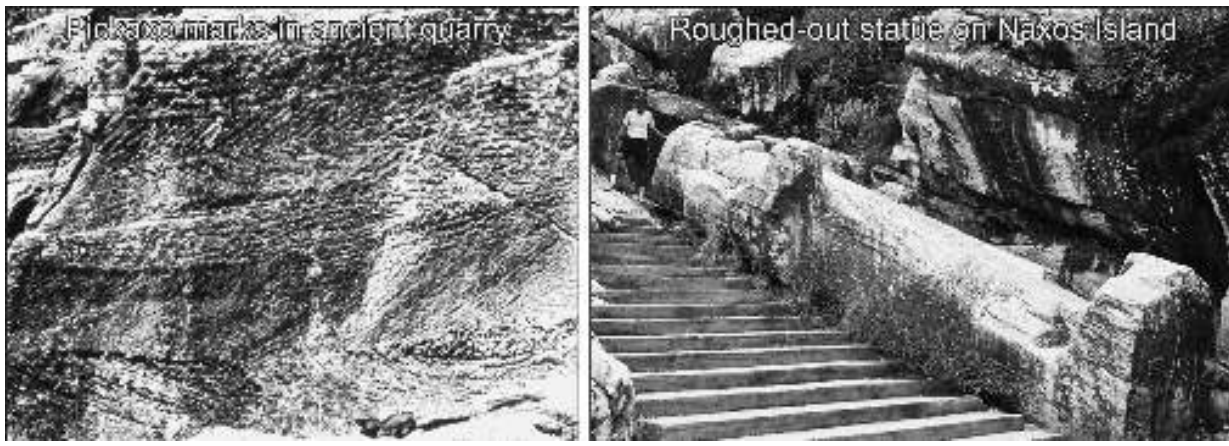


Figure 5-10: Ancient marble quarries can be easily recognized by the diagonal pickaxe marks used to cut trenches, whereas modern quarries use saws or wire loops that give smoother surfaces, or closely spaced drill holes. Larger sculptures were roughed out in the quarry, like this 10-metre-long block on the island of Naxos. Photos courtesy of the author.

identify their origin. The first step is to locate ancient quarries, which are relatively easy to distinguish from modern quarries (Figure 5-10). The next step is to associate ancient carved marble with specific quarries: Initially, this was based on simple visual inspection to estimate colour and grain size. For instance, Proconnessos marble from the Sea of Marmara is medium-grained with grey bands. Recently, more advanced methods have been used, including chemical analysis and measurements of crystal sizes, and the most successful of these methods is isotopic analysis.[214] This is based on the fact that atoms of carbon and oxygen in marble come in several different varieties, called isotopes, that have similar, but not identical, chemical properties. Earth processes can change the relative abundance of these isotopes slightly, and their ratios in a sample can be used to help distinguish similar marbles from different locations.

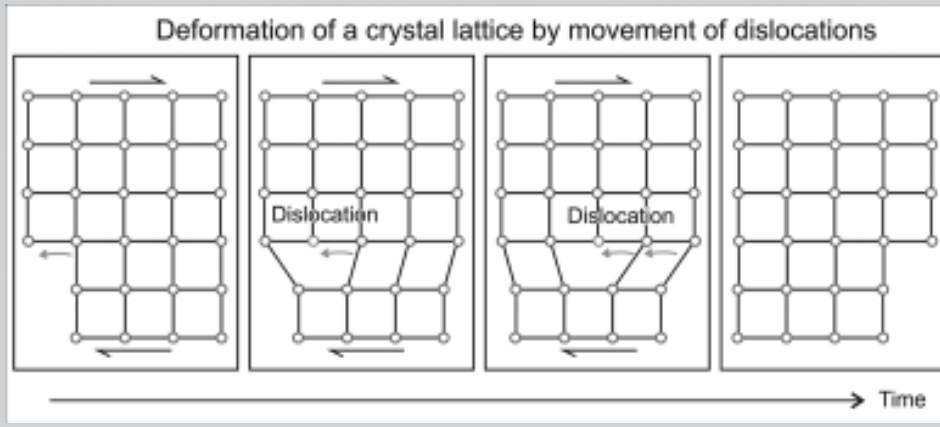
Sculpting of large statues and decorative blocks started at the quarry.[215] A suitable area of the quarry or outcrop was selected for the absence of cracks (joints), colour, and direction of foliation (grain), and a block was roughed out in place by trenching with a metal pickaxe (see box 5-4: Hard Metal Tools). Once the trench was deep enough, the block was removed using iron wedges placed in holes.

This was the riskiest part of the process and sometimes unwanted cracks developed by the release of natural stresses in the rock, ruining the block (Figure 2-21; Figure 5-10). If the block was sound, it was delivered to the sculptor, probably on or close to the final site, where carving and polishing were completed.[216] Chisels, saws, and cord-powered bow drills were used to shape the sculpture and remove material from recesses. The chisel marks were removed with an iron rasp and smoothed with blocks of emery (see box 5-5: Emery). The final polish was done with blocks of pumice, the light foamy rock produced during volcanic explosions.

Many of the decorative blocks and some of the sculptures were painted or covered with other materials, as was common in antiquity (Plate 11a). Marble was first covered with a yellowish-brown base coat, probably made from the ash of roasted bones (hydroxylapatite).[209] This material seems to have been a wash, perhaps designed to dull the bright white of fresh marble or to help adhesion of paint. The blue paint was not made from a natural pigment, as durable blue minerals are uncommon, but instead from an artificial material now called *Egyptian Blue*, which is mineralogically identical to the rare natural mineral cuprorivaite ($CaCuSi_4O_{10}$). This pigment was first made in Egypt about 2600 BCE, making it one of the first synthetic materials. Quartz sand, various copper compounds, limestone, and a small amount of soda from plant ash or *natrun* (see Chapter 2) were fired in a kiln at 800–1000°C to make a blue powder.[217] Initially, the source of copper was natural minerals such as malachite (see Chapter 7). However, traces of tin in pigment samples suggest that in later times bronze scrap was used, perhaps because it reacted at lower temperatures than pure copper. It is easy to detect even traces of this pigment, as exposure to visible light produces a strong fluorescent glow of infrared light.[218] Red paint was made from ochre, a natural mixture of minerals rich in haematite (Fe_2O_3). Ochre deposits are widespread and it is not possible to tell exactly where the red used on the Mausoleum came from. However, there were important ochre mines on Thasos and Lemnos.[170,219] One of the statues was reported

Box 5-4 Hard Metal Tools

Metal tools for cutting stone need to be hard but flexible, and it took much experimentation in antiquity to consistently fabricate metal with such characteristics.[228–230] The earliest metals to be produced, copper and gold, are soft in their pure state because of their atomic structure.



The hardness of a metal is controlled by its atomic structure.
Image by the author.

All metals are composed of crystals, in which most of the atoms are arranged in a regular structure called a crystal lattice. Commonly, some of these atomic connections are irregular and crystals deform by movements of these dislocations through the crystal lattice. In essence, when the dislocation moves, one atom is reconnected to another adjacent atom and this process can continue until the dislocation arrives at the edge of the crystal. The movement of dislocations is relatively easy in pure metals as all the atoms and their connections are the same. Metal objects can be strengthened and hardened by reducing the number of dislocations and by changing the size of the individual crystals, which is generally done by controlled heating, cooling, and hammering. However, more significant changes to strength and hardness require different approaches, which can be seen in the tool metals used extensively in antiquity: bronze and steel.

Bronze is generally made by simple mixing of refined copper and tin. This alloy is harder than pure copper because tin atoms are larger than copper atoms and obstruct the movement of dislocations in the lattice of the copper crystals. More hardening is also

produced by the development of crystals of a new metallic phase, Cu_3Sn, which also limits the movement of dislocations. However, bronze had an important disadvantage, the cost and availability of tin, meaning there was an economic incentive to develop a cheaper tool metal.

Iron ore is abundant in the earth but refining needs higher temperatures than copper or tin, hence it was developed somewhat later.[231] Early iron was made by reduction of iron oxide with charcoal and other materials, making a sponge of relatively pure iron metal that was hammered to remove the slag. Tools produced by these methods had very variable qualities and we know now that the key parameter turns out to be the amount of carbon dissolved in the iron: too little and the dislocations move easily; too much and weak crystals of graphite form in the metal. The best ancient steel had 0.2–1.0% carbon and production required the special skills of a smith to add or remove the right amount of carbon. Such metal had properties similar to modern carbon steel.

Box 5-5 Emery

Emery is a rock that contains dark crystals of corundum (Al_2O_3) set in a matrix of softer minerals, such as magnetite, haematite, and mica. Corundum is one of the hardest minerals and the gem forms—sapphire (blue) and ruby (red)—are highly valued.[232] In antiquity, the main use of emery was for polishing marble, other stones, and gems. Because corundum was held in a weak rock matrix, fresh, sharp crystals were continually exposed as the block was worn away. The emery used at the Mausoleum came from Naxos Island, where it occurs as layers in marble.[170,233] These layers originated from ancient tropical weathering of limestone, which produced red soils (bauxite) that were subsequently covered by new layers of limestone and buried deep in the earth.[234] There, the high temperatures and pressures metamorphosed the limestone into marble and the bauxite into emery.

to have been painted purple and the pigment may have been the silicate mineral glaucophane, which occurs as beach sand on Syros Island. The horses that crowned the Mausoleum were partly covered with a thin layer of metallic lead, which would have appeared dark.[209] This is an unusual application of lead, which was readily available as a byproduct of silver mining, with a major source at Lavrion, south of Athens.[170]

The Mausoleum was not an isolated structure, but part of a planned city—a new capital, its site chosen for its excellent harbour, situated beside a gently sloping area suitable for a large city. This landscape was controlled by the underlying geology.

The Site and the City

The landscape around Halicarnassus developed quite recently: hard limestone blocks on either side of the harbour resisted erosion that elsewhere created the basin and harbour (Figure 5-3). This process was especially active during the glacial period, twenty thousand years ago, when sea level was 120 metres lower than today (see Chapter 6). When the sea returned to its present level seven thousand years ago, the harbour was much larger than at present or indeed at Mausolus's time. Since then, alluvial sediments shed from the mountains to the north have filled both basin and harbour. However well-suited the landscape was, a successful city in a Mediterranean climate needed a perennial water supply.[198]

There was an important spring at Salamakis, to the southwest of the harbour—indeed the Roman geographer Strabo considered it as much an asset to the city as was the Mausoleum (Figure 5-3). The water came from rain that sank into the porous limestone up on the hill and flowed down until it met underlying impervious rocks, where it was then redirected along the interface to appear near the coast at Salamakis. The water that fed the fountain near the Mausoleum may have had a similar origin: rain sinking into the volcanic rocks that

formed Göktepe Hill was redirected to the surface by clay-rich rocks. The spring now debouches just offshore, perhaps because of changes in the height of the land during one of the recent earthquakes, or changes in the underground "plumbing" system (see Chapter 7). In any case, flow is probably less than in antiquity as urbanization prevents water from seeping into the ground.

The bedrock on which the Mausoleum was built was not ideal, but other factors, such as the spring, must have governed the choice of this site.[220] The builders removed a thin layer of alluvium covering the bedrock, which is the same sequence of volcanic and sedimentary rocks seen on Göktepe Hill (Figure 5-3). In the excavation pit, the lower clay-rich sedimentary rocks are overlain by a poorly cemented sandstone made of volcanic fragments. Several minor faults run through the site, which was also cut by numerous pre-Mausoleum galleries and chambers. The builders knew something about the necessity of good foundations and levelled some of the existing structures and intervening material, but the final excavation was a compromise with two levels: in the northeast, the sandstone bedrock was two metres higher than the clays elsewhere. Both types of bedrock are weak and would have been compressed, but not evenly, under the Mausoleum's weight—80,000 tons spread over an area 38 × 32 metres gave a pressure of 65 tons per square metre.

The site had another problem—the water table was close to the surface during the winter and the burial chamber was susceptible to flooding.[220] The builders were aware of this and constructed a tunnel around the monument to drain excess water away to the south.[198] Nevertheless, during the long history of the Mausoleum, parts of the drainage tunnel, and also the aqueduct, collapsed or became blocked by silt, and the annual water cycle resumed, flooding the burial chamber. However, this was not the worst effect on the monument: when the water table rose, clay in the bedrock became saturated, thus weakening the rock, which was not strong even when dry. In addition, the clay minerals swelled, creating a major problem for the foundations of the Mausoleum, which were forced to follow the movement

of the underlying rocks, with predictable results: the development of cracks in the building, which made the structure vulnerable to earthquake damage.

The Demise of the Mausoleum

The Mausoleum must have been largely intact in the late 12th century CE when Eustathius of Thessalonica commented that "it was and is a marvel." However, when the Knights of St. John arrived in 1404 CE to build their castle on the site of the ancient palace, it was a ruin. The roof and sections of the colonnade had collapsed, and blocks and statues that fell to the north were buried under sediments washed down from Göktepe Hill during winter storms. The culprit that started it all was likely an earthquake in 1303 CE, produced by movements along a fault to the southeast of Crete, which was felt in much of the eastern Mediterranean region (Figure 8-15; see Chapter 8).[185,221] This was the same earthquake that damaged the upper parts of the Pharos in Alexandria (see Chapter 8) and may have loosened the pyramids' casing blocks, enabling wholesale looting of this fine limestone (see Chapter 2). Although this earthquake was powerful, it was far from Halicarnassus and local shaking would have been relatively small—suggesting that the Mausoleum must have already been in a weakened state, to have collapsed the way that it did.

A solid structure like the Mausoleum, or the Pyramids, may seem to be more resistant to earthquakes than a temple, but this depends not only on the quality of the foundations but also on how well anti-seismic construction methods were applied. In most ancient temples, blocks were tied together with iron clamps, set in lead, so that the whole structure moved as one during earthquakes or settling. Although many blocks from the Mausoleum still have traces of clamps, it is not at all clear that all 160,000 blocks were secured—this would have required a huge investment of time and money. Second, as was mentioned before, the foundations were shallow and the whole

structure rested on weak rocks that were inundated during winter rains, causing it to move and crack.[220]

Another earthquake in 1493 CE may have completed the Mausoleum's destruction and also damaged the Castle of the Knights of St. John.[185] We do not know where the earthquake was centred, but there are no reports of damage from elsewhere, so it may have been close. A year after the earthquake, the knights started systematic demolition and quarrying of the Mausoleum's ruins to rebuild their castle (Figure 5-11). They used large numbers of the blocks of greenish volcanic tuff from the Mausoleum and pink porphyry from the courtyard walls. They even incorporated larger sculptures from the Mausoleum into the walls, from which some were later recovered and sent to the British Museum (Plate 10b).[390] However, smaller marble fragments were roasted to make lime for mortar (see Box 4-4: Stucco and Frescoes). The demolition took a long time as the burial chamber was only found in 1522 CE. Although it was rumoured to have still been intact and robbed the night after its discovery, in actual fact the grave was plundered in antiquity, probably shortly after it was finished, and it is unlikely that anything of value remained.[222] It is paradoxical that in this same year the Ottoman Turks defeated the knights at their headquarters in Rhodes and soon after the Bodrum Castle was surrendered without a fight. The castle is now a maritime museum, where excavated remains of ancient shipwrecks are displayed, including the Kızılburun wreck (see box 5-3: An Ancient Marble-Carrying Ship).

In 1856 Charles Newton rediscovered the site of the Mausoleum while working for the British Museum.[223] The initial results of his excavations were disappointing, as the knights had been efficient at demolishing and plundering the tomb. Eventually, Newton excavated a deeper section on the north side of the Mausoleum, where he found large amounts of broken sculpture and architectural blocks that had escaped the knights' depredations (Figure 5-12). The sculptures were sent to the British Museum, but the Royal Navy took the undecorated blocks to build a naval dockyard in Malta, echoing the knights' reprehensible acts four hundred years earlier. The appearance of the

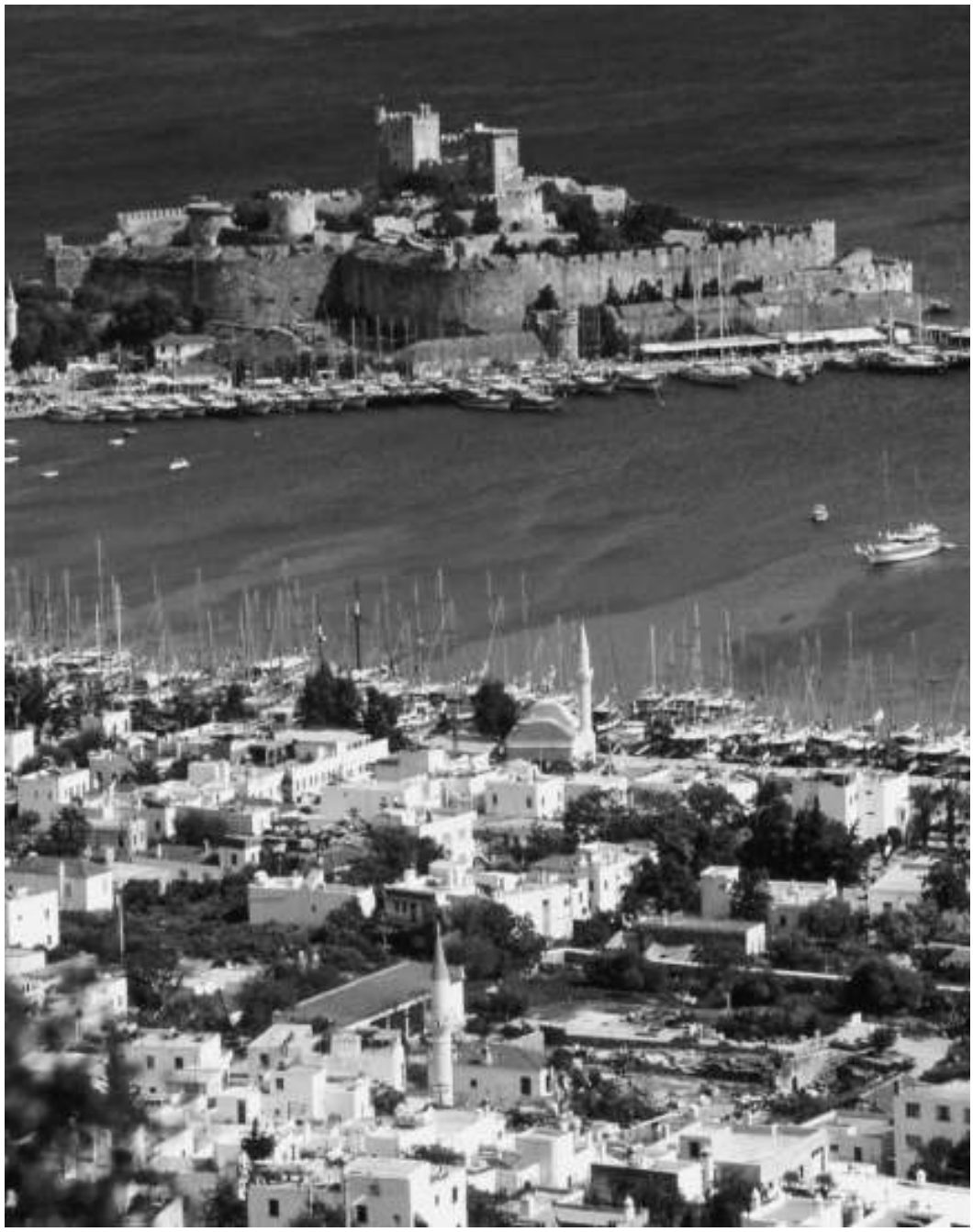


Figure 5-11: The Knights of St. John built their castle on a former island that was the site of the Palace of Mausolus. It was constructed using blocks from the palace and rebuilt with material from the Mausoleum, whose foundations are visible in the foreground to the right of the lower minaret. Photo courtesy of the author.

Figure 5-12: The Mausoleum was first excavated by Charles Newton, seen here to the right of a Royal Navy sailor, surveying blocks originally from the Mausoleum's roof. Newton, C.T. and R.P. Pullan, 1862, *A History of Discoveries at Halicarnassus, Cnidus & Branchiae*. Day & Son: London.

Mausoleum was largely recreated from these materials and the sculptures formerly incorporated into the castle walls. When Newton left the excavation site in 1859, he summed it up as "A desolate looking spot, of which the idea is finer than the reality." A Danish expedition resumed excavations a century later and cleared the site down to the burial chamber and foundations that we see today.[211]

Mausolus has left a legacy, even if his magnificent tomb no longer survives—the concept and the word *mausoleum* exist to this day in different cultures and languages. Finally, if we recall Lucian's "Conversation in Hades" (see box 5-1: Conversation in Hades), we may perhaps conclude that Mausolus finally scored a point in his argument with Diogenes, as more people have come across the word *mausoleum* than the philosophy of Diogenes.

6

The Temple of Artemis at Ephesus

The Temple of Artemis

> I have gazed on the walls of impregnable Babylon along which chariots may race, and on the Zeus by the banks of the Alpheios [Olympia], I have seen the Hanging Gardens, and the Colossus of the Helios, the great man-made mountains of the lofty Pyramids, and the gigantic tomb of Mausolus; but when I saw the sacred house of Artemis [Ephesus] that towers to the clouds, the others were placed in the shade, for the Sun himself has never looked upon its equal outside Olympus.
>
> Antipater of Sidon ~140 BCE (Greek Anthology IX.58)

The story of Ephesus is not only that of the three successive Temples of Artemis, the last of which was one of the Wonders of the World (Figure 6-1), but also of the city that grew up nearby and became the second-most populous urban centre in the Roman Empire. Of the wondrous temple, there is almost nothing left now, so we can only make educated guesses as to what it may have looked like starting with ancient writings. One such description was by Pliny the Elder, writing in the first century CE:[25] "The most wonderful monument of Grecian magnificence, and one that merits our genuine admiration, is the Temple of Diana [Artemis] at Ephesus, which took one hundred and twenty years in building, a work in which all Asia [Minor]

Figure 6-1: The fourth century BCE Temple of Artemis was the largest in the Greek world—122 metres long and 65 metres wide at the base of the terrace—with a cult statue of Artemis in an interior courtyard open to the sky. Sacrifices were performed in front of the temple on an altar enclosed by a colonnade. A basin originally fed by a sacred spring lay in front of the altar court on the right (not shown). Image by author after a model in Ephesus Museum, Selçuk.

joined. . . . The entire length of the temple is four hundred and twenty-five feet, and the breadth two hundred and twenty-five feet. The columns are one hundred and twenty-seven in number, and sixty feet in height, each of them presented by a different king. Thirty-six of these columns are carved." We can add to this rather sparse account, which may be a conflation of the wondrous temple and its predecessor, using contemporary coins (Figure 6-2) and excavation reports.[235–237]

The greatest Temple of Artemis was at Ephesus on the Aegean Coast of Turkey (Figure 6-3). Construction began in 323 BCE with the creation of a stepped platform several metres above the surrounding area, which enhanced the height of the temple and protected it from flooding. The 127 columns were 18 metres high and 1.5 metres in diameter, with those on the front resting on sculpted bases, an unusual

Figure 6-2: The reverse side (tails) of these two Roman silver coins have images of the temple and statue. On the left coin, the columns of the temple were schematically reduced to four but the pediment at the top is shown in detail, with three openings and four figures (41-42 CE tetradrachm, DIAN[A] EPHE[SUS], Emperor Claudius). On the coin to the right, the front of the temple is shown with the correct number of columns flanking a statue of Artemis (Diana) with garlands in her hands (EPHESION, Emperor Hadrian, 117–138 CE). Wood, J.T., 1877, *Discoveries at Ephesus, Including the Site and Remains of the Great Temple of Diana*. Longmans, Green and Co, London.

feature (Figure 6-4). The temple was roofed in the usual way but with a central courtyard open to the sky. The principal cult figure of Artemis was probably placed in a smaller temple within the courtyard. The western pediment had a central window with doors that may have been used to show another cult figure, perhaps during ceremonies at the altar. It was flanked by two other openings and four statues—probably of Amazons, the legendary female warriors who were considered by the Greeks to be the founders of the city. The interior of the temple must have been equally impressive, as ancient writers tell of columns guided in silver and gold, paintings and religious statues by famous sculptors—but alas nothing of this remains.

A courtyard with an altar lay 20 metres west of the temple (Figure 6-3).[238] It was walled on three sides and a colonnade was added later. Strabo said that it was filled with sculptures by Praxiteles, one of the most renowned artists of the time, a great motivation for the first

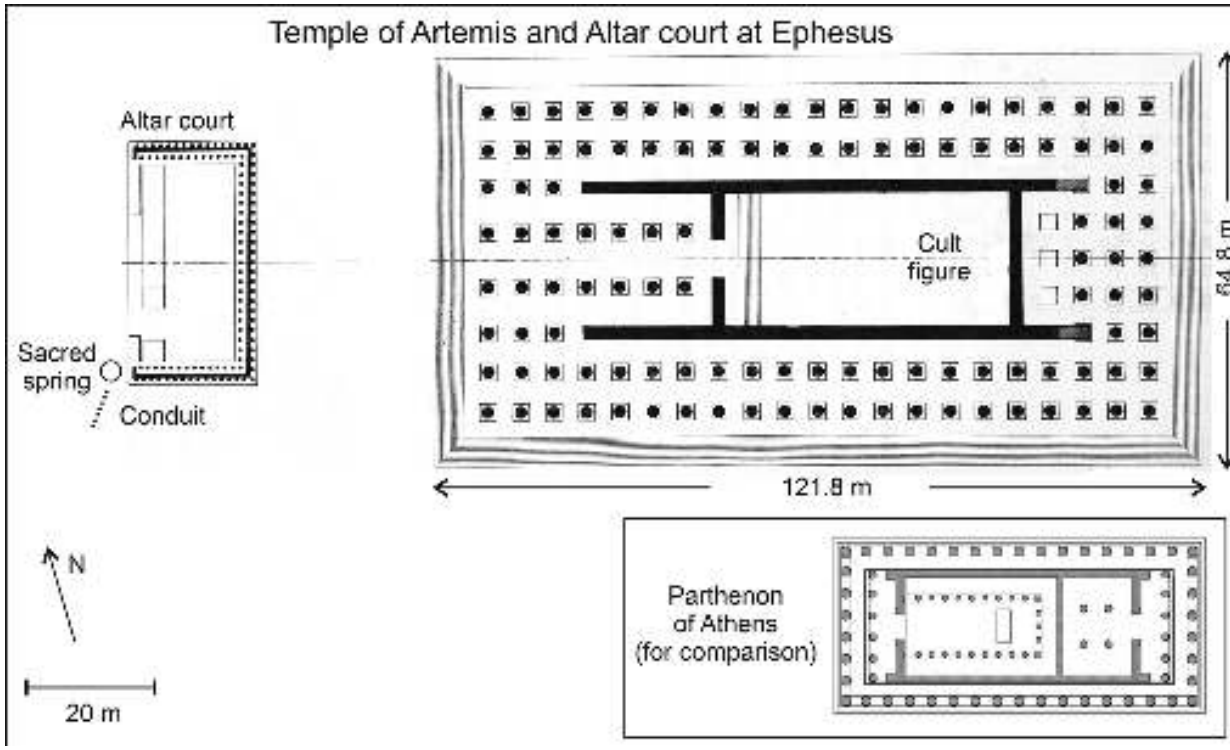


Figure 6-3: The sacrificial altar was enclosed in a substantial building and the main temple was even more impressive—almost twice the size of the Parthenon of Athens, in height, length and width. Image by author after Bammer, A., 1972, *Die Architektur des jüngeren Artemision von Ephesos*. F. Steiner: Wiesbaden.

excavators, but nothing was found. Sacrifices to Artemis were conducted there, under a statue of the goddess in the central window of the pediment (Figure 6-1).

A basin holding water from a sacred spring lay in front of the altar court (Figure 6-3). Beside the basin, the excavators found a substantial conduit made of lead pipes with marble collars, dating from the 5th or 4th century BCE, perhaps fed from an aqueduct[239] (Figure 6-10).

The platform, temple, and altar court were built almost entirely of white marble. Even the roof was covered with marble tiles up to 1.3 metres wide, with smaller ceramic tiles to bridge the gaps. What is interesting here is the extensive use of marble as it took considerably more work to shape this rock when compared to the limestone that was more typically used for religious buildings, which speaks to the importance of this temple in the eyes of the ancient Greeks.

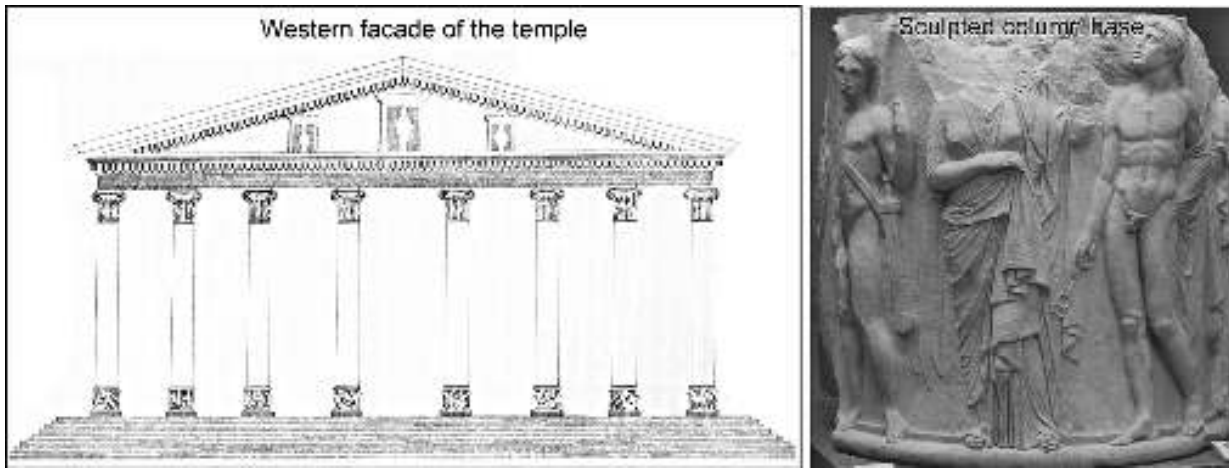
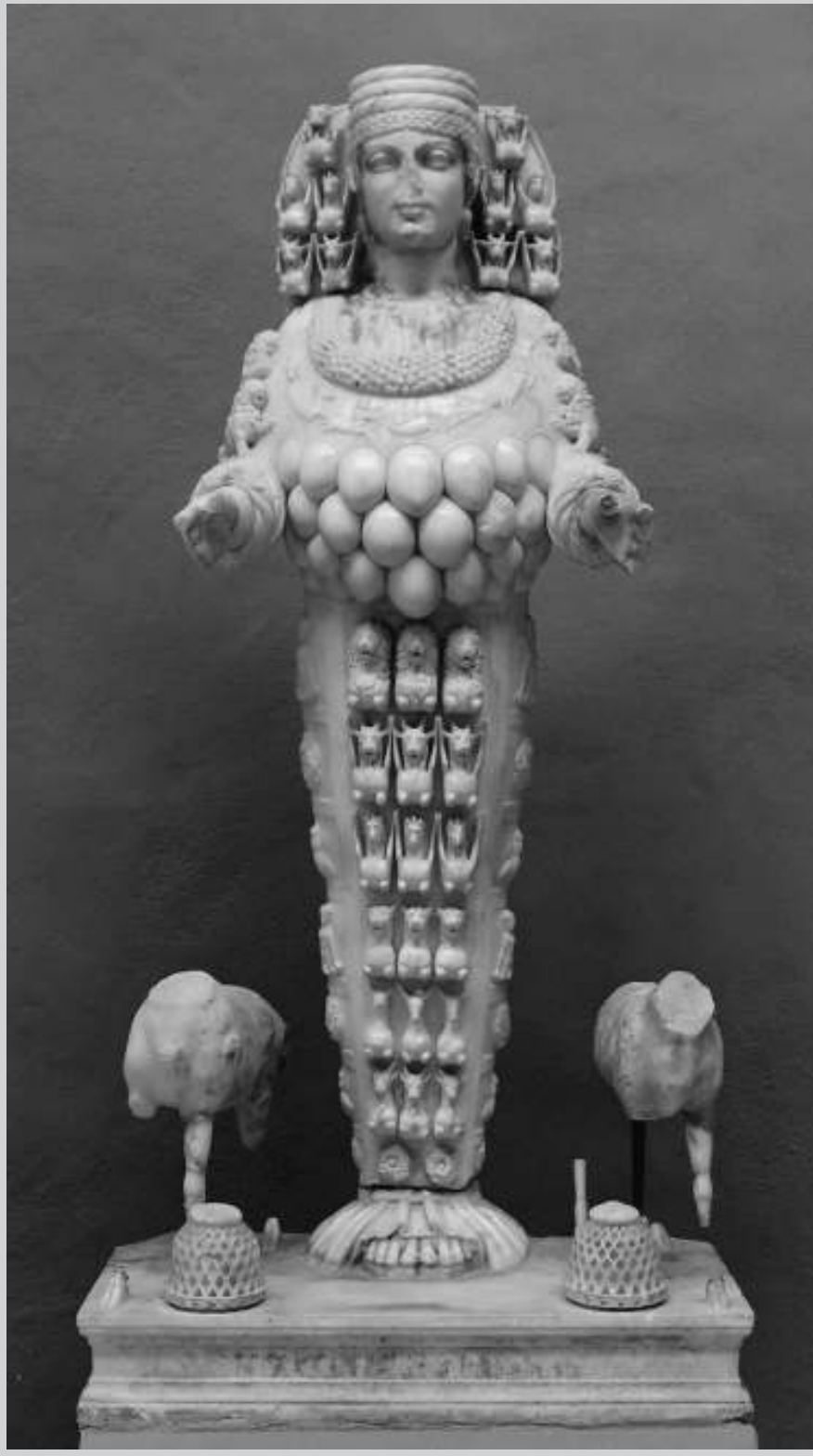


Figure 6-4: Columns at the front of the temple had unusual sculpted bases and possibly larger than normal decorated capitals. Only one base has survived intact, carved with human-sized figures from mythology. Image after Bammer, A., 1972, *Die Architektur des jüngeren Artemision von Ephesos*. F. Steiner: Wiesbaden. Photo © Twospoonfuls / Wikimedia Commons / CC BY-SA 4.0.

Artemis was the most popular deity of the Greco-Roman pantheon (See box 6-1: The Cult Figure of Artemis). Like most immortals, she was an amalgam of different traditions and regional goddesses, both a nature goddess, inherited from Cybele and other sources, as well as a hunter. But most importantly, she was the goddess of childbirth, fertility, and—chastity! People have often tried to integrate these traditions into a coherent whole. However, it seems likely that the ancient Greeks would have found this process difficult to understand and indeed somewhat pointless.[240] They were content with many diverse and sometimes contradictory traditions, and maybe we should be as well.

As the renown and wealth of the cult increased, the temple and altar became the focus of a community, built to accommodate the priests in their religious and business activities.[241] The temple and its surroundings were a refuge, where people could demand protection, although this did not always work in practice—Arsinoë, the sister of Cleopatra, was executed there on the orders of Marcus Antonius (Mark Antony). The sanctuary was full of votive offerings and also acted as a secure deposit for valuables and important documents. The

Box 6-1 The Cult Figure of Artemis



A first century CE Roman cult statue of Artemis (Diana). Photo © Gargarapalvin / Wikimedia Commons, CC BY-SA 4.0.

The cult figure of Artemis changed enormously during the 1,400 years that she was worshipped at Ephesus. The first figures may have been simple wooden images, reflecting the original nature goddess Cybele. However, with time the cult statues became more elaborate, terminating in the complex statues of the Roman period.[156] At that time, the temple had a team of female officials to dress the cult figure. The main statue may, in fact, have been a reliquary for an older wooden image, rather like the elaborate mediaeval containers that house the bones of saints.

Although the original cult statue has not survived, there are many copies from this period that are somewhat similar. Her head is quite normal, pale or occasionally black, and may carry a reliquary or building model. Her upper body is surrounded by several rows of pendulous objects, which have been interpreted as breasts, fruit, bull's testicles or other things. Her lower body is reduced to a conical tube covered with animals and her feet, partially wrapped in cloth, protrude from the base. In some statues there is a model of a small temple or a reliquary on her head. The cult figure is quite unlike anything from elsewhere and has proved to be a rich ground for speculations on the origins of the various parts. Perhaps it is best to think of it like modern statues of saints in Orthodox churches, which can be elaborately dressed and ornamented.

temple also had large landholdings in the fertile Cayster Valley, including fish and animal farms. Every year, it hosted a month-long festival in honour of the goddess and every four years there were athletic and cultural games, similar to those in honour of her father Zeus at Olympia (see Chapter 4).

The wondrous temple was the last in a series of sanctuaries at Ephesus. The first was probably sacred to Cybele, an Asiatic nature goddess, and there may have been buildings there as early as the 10th century BCE, probably centred around a spring that debouched on low-lying land to the southwest of the hill, close to the ancient shore.[242] Such a spring would have been important to both mariners and the inhabitants of the region as it gave clear, fresh water all year

round, in contrast to the brackish and muddy water of the Cayster River and estuary.

When the Greeks arrived, they adsorbed Cybele into their goddess Artemis and built a small temple, which was destroyed by a flood in the 7th century BCE.[243] Such floods, and the sediments that they deposited, became a recurrent theme in the history of the sanctuary. Excavation of this temple revealed ivory, bronze, and ceramic remains so the cult of Artemis was thriving at that time. A particularly intriguing find was a collection of optically reducing lenses made of polished quartz.[235] Similar lenses have been found elsewhere in the Aegean and may have been for the correction of myopia.

A second temple was started around 550 BCE, built on a low platform above the alluvial plain. It was the first large building entirely constructed of marble[244] and was considered the most impressive temple in the Greek world at that time. It was partly funded by Croesus, the Lydian king whose legendary wealth was derived from abundant placer gold deposits (see Chapter 4) found in the rivers around Sardis, 70 kilometres northeast of Ephesus. He was also famous for introducing standardized pure gold and silver coins (see box 6-2: Money and Minting).

In 356 BCE a fire burned the rich furnishings, oil-soaked offerings and wooden roof beams of the temple. The intense heat cracked the marble walls and columns, converting parts to powdery lime, resulting in the partial collapse of the temple. A local man, Herostratus, declared under torture that he had started the fire because he wanted his name to be immortalized, but like all such confessions it should be regarded somewhat sceptically. Curiously enough, blame was also placed on the goddess, who, it was said, had abandoned her temple that night to supervise the birth of Alexander the Great.

Construction of the third and final temple started in 323 BCE on the same site from new materials, as almost nothing could be recuperated from the burnt ruins of the older building. One of the architects was said to be Deinocrates, who had planned and constructed the city of Alexandria, the future site of the Pharos. The new building—slightly larger than the earlier temple and built on a yet higher platform—was

Box 6-2 Money and Minting

Gold coin, weight 10.7 g, King Croesus of Lydia, 564-550 BCE.
Photo © Classical Numismatic Group, Inc / Wikimedia commons, CC-BY-SA 2.5.

Civilization existed without money for thousands of years: indeed, two of the wonders were built during this period, using barter or payment in kind and metal ingots (bullion) for larger transactions. However, the limitations of such a system are obvious and coins made of electrum, an alloy of gold and silver, first appeared in Lydia (western Turkey) in about 650 BCE.[273]

It used to be thought that "white gold" was used because it was the composition of metal grains in the abundant placer deposits in the region (see Chapter 4), but it now appears that the alloy was deliberately made from pure gold and silver. The value of silver is much less than that of gold (1:10 to 1:14 in antiquity) so from the very start, there was a problem with the variable composition of such coins although their weight was carefully controlled. Electrum may have been used for coinage because it is five times harder than pure gold or silver, and hence more resistant to wear or it may have been to "stretch" valuable gold supplies. We know that such coins were not welcome everywhere: for a long time, the Temple at Ephesus only accepted pure bullion for donations and debts. It was only when the Lydians under King Croesus (561–547 BCE) started to issue standard weight coins of pure gold or silver that monetary transactions became more important.[274] The legend of the exceptional wealth of Croesus may well have been inspired by this innovation, rather than riches much greater than his predecessors or neighbours.

The metal in many placer deposits contains silver and sometimes copper, which must be processed to separate the pure metals. The Lydians knew how to do this long before electrum coins were minted and although we do not know the details, it was probably based on a simple chemical process now called cementation.[275,276] Gold, in the form of dust or thin sheets, was sealed in a pot with salt and brick dust. When red-hot, the salt emitted chlorine gas that combined with the silver to make silver chloride that then evaporated and was absorbed into the brick dust and the pot walls. The residual gold was picked or panned from the debris.

Most silver was not derived from placers but was produced from galena (PbS), a lead mineral that commonly contains small amounts of the metal. Galena was extracted from the ore and heated to drive off sulphur, leaving behind metallic lead. Air was then blown over the molten metal, oxidizing the lead but not the silver, which remained as droplets floating on the molten lead oxide. Metallic lead was recovered by smelting the oxide with charcoal. Some silver was also recovered from cementation process waste using a similar process: the brick dust was heated with metallic lead making a silver-lead alloy that was purified as above.

Nobel metals were cast into coins with fixed weights and stamped with identification marks. Electrum and gold coins had a very high value and must have only been used for major transactions. Later on, silver coins became more important as they could be used for a wider range of purchases. Nevertheless, they still had a high value: the famous four-drachma silver coin of Athens, made from 512 BCE, could buy 30–40 kilograms of wheat. Later still, coins made of copper or bronze became widespread for more mundane uses. In most cases, the value of the coins equalled the value of the metal from which it was made, a link that has been lost recently in modern currency.

an immediate success and was soon recognized as one of the Seven Wonders of the World. Under the Romans, who subsumed Artemis into their goddess Diana, the power of the shrine and its cult increased even more—its success, and that of nearby communities, was due, in part, to the geography of the site.

The Temple Site and the City of Ephesus

When the Temples of Artemis were constructed, they stood close to the waters of a large, narrow bay, into which flowed the Cayster (now Küçük Menderes) River (Figure 6-5).[245] This was an ideal harbour, sheltered from the dominant north winds both by the hills to the north and also by a long island in the gulf itself. Such a harbour was well suited for the development of trade—both along the coast and down the valley from the interior of the continent (see box 6-3: The Aegean Coast of Turkey). Another attraction of the site must have been agricultural: the broad Cayster Valley was watered by a perennial river, and erosion of soil in the mountainous interior brought down a fresh load of muddy sediments each year that fertilized the fields. This overall interface between sea and land echoes a founding myth of Ephesus: that a fish would point the way to the future site of the city and that a boar would lead the way overland.

The Temple of Artemis stood just south of an elongated hill (site of modern Ayasoluk) made of marble and schist (Figure 6-5). The steep west side of the hill follows a fault and the relief here may have been partly produced by movements during prehistoric earthquakes, as happened elsewhere in the region (Figure 6-5).

The builders of the temple were well aware of the dangers of earthquakes, both local and distant. Pliny recounts that "A marshy soil was selected for its site so that it might not suffer from earthquakes, or the chasms which they produce. On the other hand, again, that the foundations of so vast a pile might not have to rest upon a loose and shifting bed, layers of trodden charcoal were placed beneath, with fleeces covered with wool upon the top of them." The location of the site, close to active faults, means that anti-seismic construction methods had to be used if the temple was to withstand earthquakes, but did the measures described by Pliny provide useful protection?

Unfortunately, they did not. Constructions on marshy sites are, in fact, generally more susceptible to damage during earthquakes. This

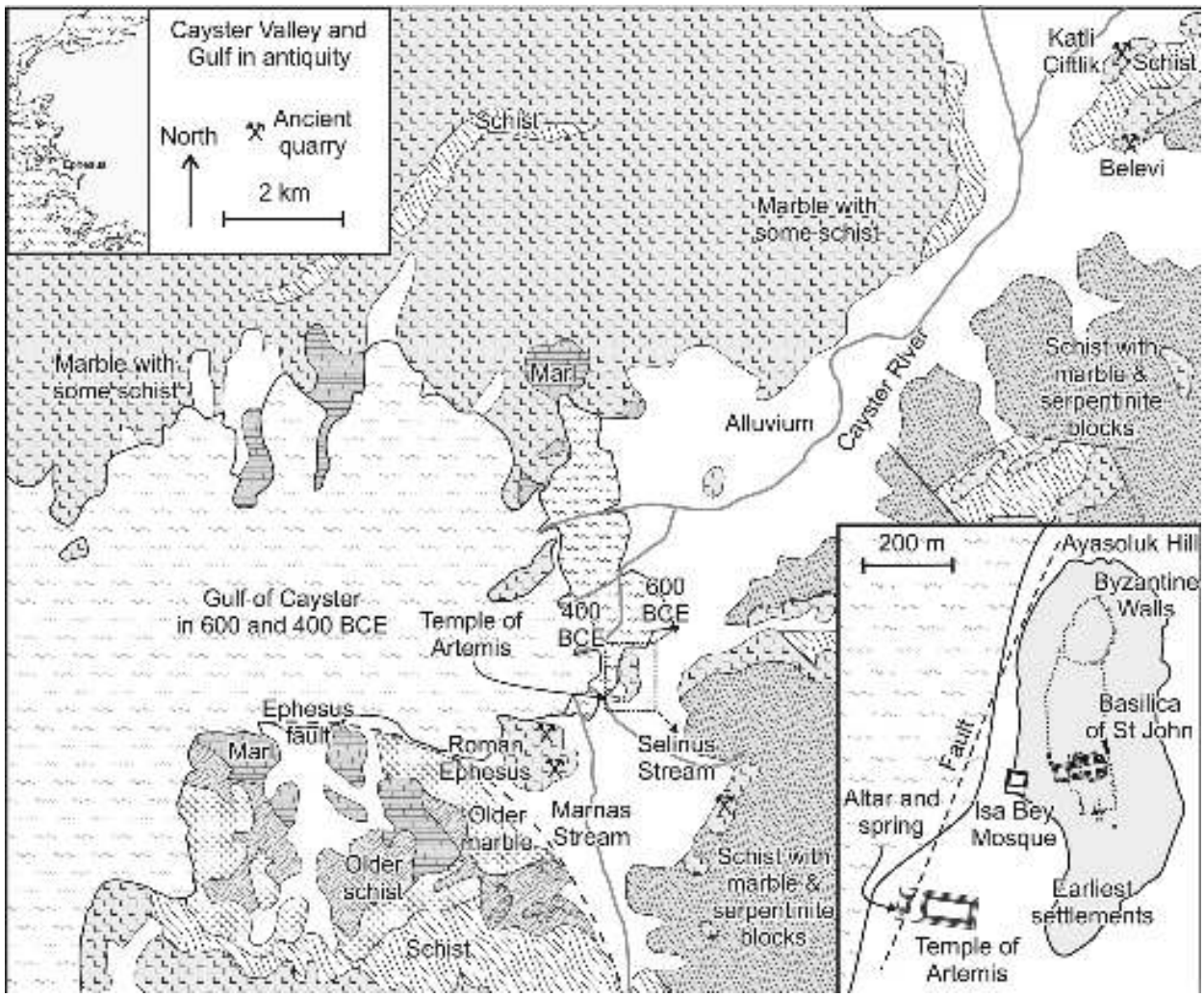
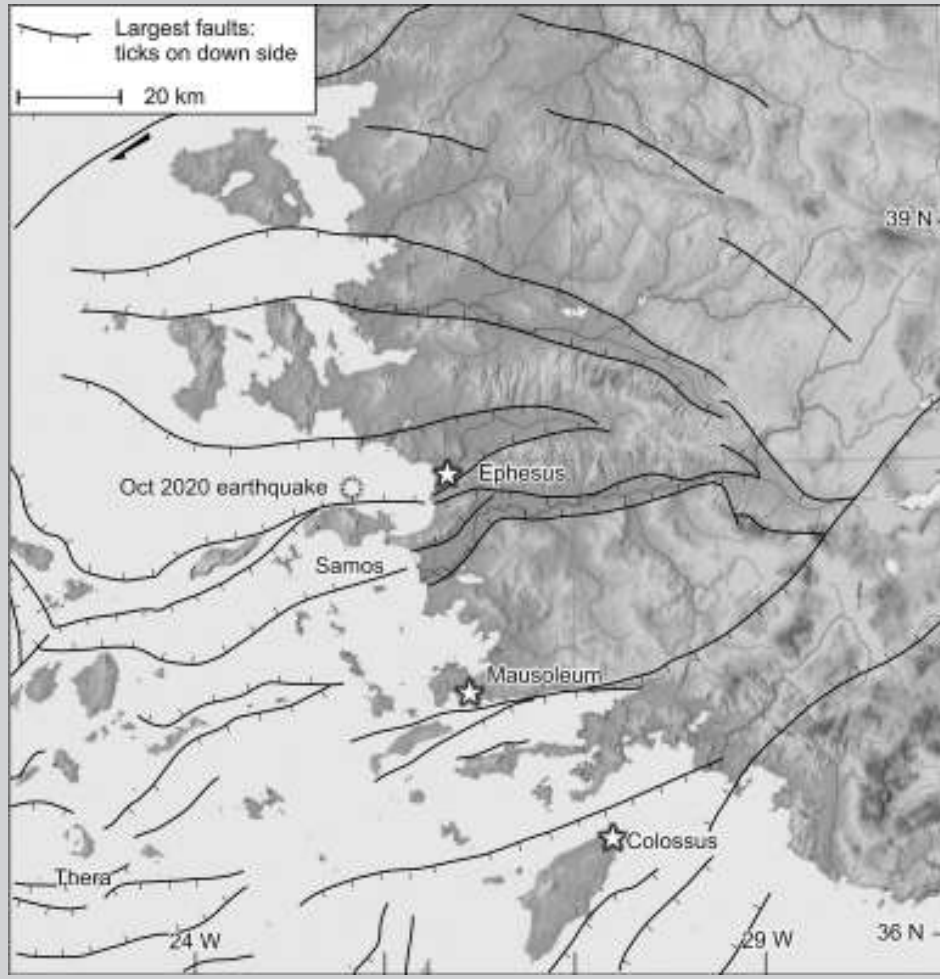


Figure 6-5: The Temples of Artemis were built on a coastal site at the bottom of the ancient Gulf of Cayster. Map by author after Brückner, H., et al., 2017, "Life Cycle of Estuarine Islands—From the Formation to the Landlocking of Former Islands in the Environs of Miletos and Ephesos in Western Asia Minor (Turkey" *Journal of Archaeological Science: Reports* 12: 876–894; Yavuz, A.B., M. Bruno, and D. Attanasio, 2011, "An Updated, Multi-Method Database of Ephesus Marbles, Including White, Greco Scritto and Bigio Varieties." *Archaeometry* 53(2): 215–240.

is because the loose sediments can resonate like a bell, amplifying the seismic vibrations. In addition, if the sediments are saturated with water, then the soil can liquefy like quicksand and buildings can sink into the ground. A layer of charcoal and fleeces may have been intended to drain the site, in a similar way that modern geotextiles are used to stabilize soil, but this seems unlikely to have been very effective. In any case, there is no archaeological evidence for these materials

Box 6-3 The Aegean Coast of Turkey



Eastern Aegean and western Turkey are dissected by numerous faults defining east-west valleys that have helped control the development of three of the Wonders. Image by author after Kreemer, C. and N. Chamot-Rooke, 2004, Contemporary kinematics of the southern Aegean and the Mediterranean Ridge. *Geophysical Journal International* 157(3): 1377–1392.

Ephesus lies at the end of a major valley that extends eastwards into the interior of Turkey, one of many similar valleys and intervening ridges all along the Aegean Coast of Turkey. Some of these structures extend westward into the Aegean Sea, where the higher parts of the ridges are islands. This landscape was produced by large-scale crustal forces during the last twenty million years[277,278] Dominantly north-south stretching of the earth's crust broke it up along long faults into east-west slices. Some blocks descended to make grabens, whose surface expression are rift valleys, and others were forced upwards to form

ridges. This stretching is more intense to the west under the Aegean Sea, where the crust is so thin that its surface is mostly submerged (see Chapter 1). The stretching continues today and many of these faults have moved in historic times generating powerful earthquakes.

These stretching forces are part of the overall plate tectonic movements of the eastern Mediterranean region. To the south of the Aegean, the convergence of the African and Eurasian plates forced the floor of the Mediterranean Sea downwards deep into the earth at an angle of about 45 degrees. With time, this "hinge" rolled southwards stretching the rocks above the slab, making the east-west valleys and underwater chasms of the Aegean region. As for the slab itself, when it reached a depth of about 100 kilometres, parts of it melted and the magma rose to the surface to feed volcanoes, such as the one that forms the island of Thera (Santorini).

The rift valleys of western Turkey had an important effect on ancient overland trade, guiding it to the harbours at Ephesus and elsewhere. Maritime trade was also determined by the islands and coastline produced in response to this stretching—trade along such routes contributed financially to the building of the Temple at Ephesus as well as the Mausoleum and the Colossus.

and the site of the temple was already covered with the debris of two earlier temple.[247] The most effective anti-seismic measures used in the construction of the temple were probably similar to those applied elsewhere at the time: the marble blocks were tied together with bronze or iron clamps, set in lead. As for Pliny's comment about chasms, it is true that major earthquakes may produce cracks at the surface, and the temple was built close to a postulated fault, but there is no documentary or physical evidence for historic fault movements near the temple.

The importance of the spring near the altar should not be underestimated—it may have guided the location of the original settlement and sanctuary (Figure 6-3). The spring was probably fed by rain that fell on Ayasoluk Hill, drained into the soil and was channelled along fissures developed in the limestone by solution (see Chapter 4). The water then flowed to the southwest and was channelled to the

surface along the fault, the same one that follows the precipitous western slopes of the hill (Figure 6-5). This spring may be one mentioned by Strabo and called *Hypelaeus*, which means "oily." The oil may have come from the limestones, which commonly contain small amounts of petroleum, or from decaying vegetation. The spring's natural flow rate was never high and in the 6th century BCE a conduit and aqueduct were installed to compensate for this problem (Figure 6-3).[248] Now, the spring does not flow at all, probably because urbanization on Ayasoluk Hill has reduced the adsorption of rainwater into the bedrock.

Not everyone is convinced that the Hypelaeus spring was near the sanctuary and some have proposed that it may have been north of the Roman city where the remains of the "Crevice Temple" now lie (Figure 6-6). Here, a deep fissure in the bedrock may have once been a spring but there are none of the calcareous deposits called tufa that tend to form where subterranean waters issue from marble or limestone.[249]

The Roman city of Ephesus stood a few kilometres southwest of the Temple of Artemis on two hills of marble and schist. The most important street of the city ran up the valley between the hills close to the route of the Ephesus Fault (Figure 6-5). This fault is considered to be active as it has moved during the last ten thousand years but not apparently during the history of the city.[250] It is movements on this fault, probably related to overall north-south extension of the crust, that has produced the steep slopes to the south of the city (Plate 12a) (see box 6-3: The Aegean Coast of Turkey).

The temple and surrounding early settlements were built beside an alluvial plain that was particularly susceptible to flooding and sedimentation (Figure 6-5, Figure 6-6).[251] The hills surrounding the plain are made of schists with marble and serpentinite blocks, weak rocks that are easily eroded. In addition, a valley to the south was formed by the erosion of rocks fractured during movements of the Ephesus fault. Winter storms could easily mobilize all these materials, which were then transported by the Selinus (now Derbent) and the Marnas (now

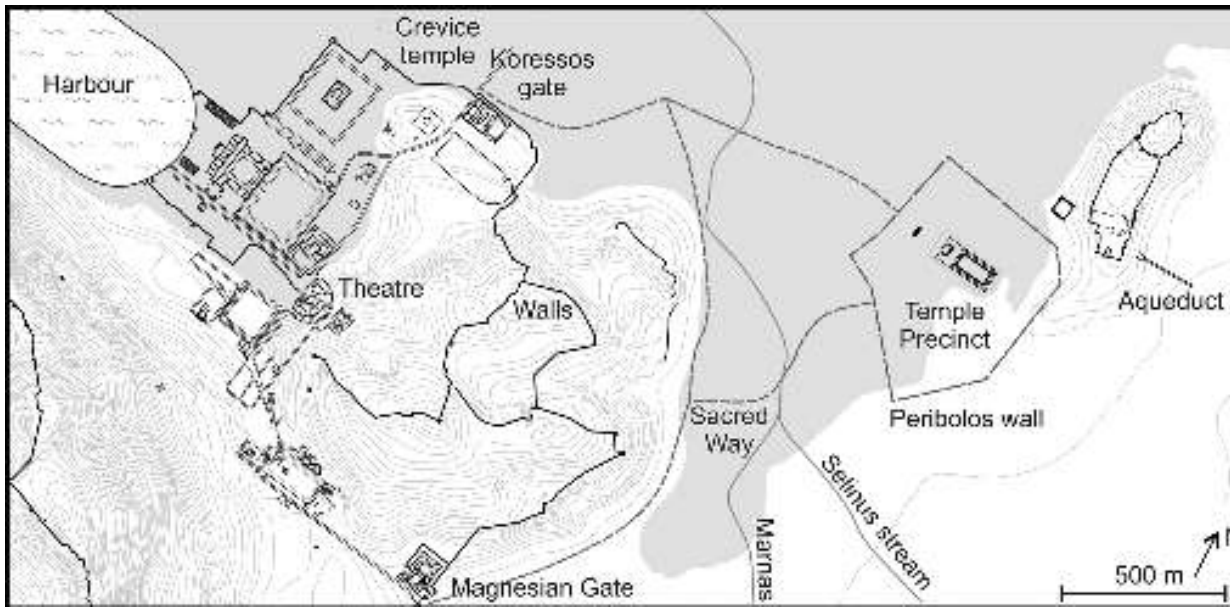


Figure 6-6: Partial excavation plan of Ephesus. The temple was found by tracing the sacred way from the Magnesian Gate to the precinct. The positions of the Selinus and Marnas streams are those at the time of the excavations in the 1870s. Map by author after © Marsyas / Wikimedia Commons, CC BY 3.0; Wood, J.T., 1877, Discoveries at Ephesus, Including the Site and Remains of the Great Temple of Diana. Longmans, Green and Co. London; Scherrer, P.G., L. Bier, and G.M. Luxon, 2000, Ephesus: The New Guide. Ege Yayinlari: Istanbul.

Değirmen) Streams to the plain, where they were deposited as the water lost its force. Such events were so frequent that a wall was eventually erected around the sacred compound to keep it clear of debris. Despite these problems, the local geology contributed an essential resource for the development of the sanctuary: marble.

Marble for the Temple

The last two Temples of Artemis needed large numbers of big blocks of pale marble that could not be supplied by the small quarries of thinly bedded dark marble that can be seen near the temple site (Figure 6-5), so a more distant source was used. The Roman writer Vitruvius [244] wrote that quarries near Belevi, 15 kilometres to the northeast were opened to build the temple (Figure 6-5). This was certainly a convenient location for quarries as the stone could be moved

down river, probably on rafts, as was done elsewhere (see Chapters 2 and 3, Plate 7a).

We can verify this origin by analysis of marble fragments from the site of the temples and known ancient quarries in the region[246,252] (see Chapter 5 for isotopic identification methods). This showed that the second temple was indeed built using marble from a single quarry near Belevi. However, marble for the third temple, the Wonder, was taken from a nearby quarry on the other side of the hill at Katli Çiftlik.[253] The polygonal paving of the altar court appears to have been recycled from blocks cut for the second temple, perhaps to give continuity with the earlier temple (Figure 6-1). I talk about how marble was shaped and polished in Chapter 5, but here I want to consider how marble and schist, the rock associated with it, were formed (Figure 6-5).

Marble and schist are metamorphic rocks that were produced from limestone and shale (mudstone) by the action of the high temperatures and pressures that occur deep in the earth. The original sedimentary rocks formed at the surface and were forced downwards by the simple accumulation of younger rocks on top or by compressive tectonic forces. In places like the Aegean, such metamorphic rocks are widespread at the surface. They have returned to the surface by erosion of overlying rocks and more importantly as a result of tectonic forces that have stretched parts of the crust and cut it up into fault-bounded blocks.

Metamorphism may change the mineralogical composition of the rock as well as the size of its existing crystals (see box 6-4: Coloured Marble and Other Decorative Stones). For limestones, the most evident effect is the recrystallization of calcite ($CaCO_3$) and dolomite ($CaMg[CO_3]_2$): in the original rock these crystals are generally invisible to the naked eye, whereas in marble they are typically 1–4 millimetres long. These carbonate minerals cleave easily, giving shiny surfaces that glint in the sun—indeed, the word marble may be ultimately derived from the ancient Greek verb marmaírō, "to sparkle." As the carbonate grains grow, they push aside smaller grains of impurities, such as iron oxides, clay, and organic materials, and the rock

Figure 6-7: A pale marble was used to construct all parts of the temple. Here, part of the sculptural column drum from the third temple has been weathered so that the different minerals stand out: the pale areas are calcite and the darker, raised areas are dolomite, which is harder and less soluble in water. Photo courtesy of the author.

becomes paler (Figure 6-7). Metamorphism can also transform some impurities into new minerals that are more stable at higher temperatures and pressures. For example, in limestones, carbon derived from living organisms is converted into graphite, which darkens marble, and clay minerals are transformed into the shiny mineral mica, making a greenish marble. If clay minerals are abundant, such as in shales, then the metamorphic rock schist is formed, named for the ease with which it splits into sheets.

At the high temperatures and pressures necessary for metamorphism, marble is weak and over time deforms like modelling clay ("plasticine"). Cracks and holes in the original limestone close up, although their former presence is commonly revealed by dark streaks, patches, and lines, which are richer in impurities. In some situations,

Box 6-4 Coloured Marble and Other Decorative Stones

The Romans used coloured marble and other stones from throughout the Mediterranean and a good selection can be seen in the columns that line the streets of Roman Ephesus[279] (Plate 13b). One of the most popular was a green, striped marble from southern Evvia (Greece) called *Marmor Carystium* (*Cipollino* = "Onion"). The pale areas are rich in calcite and the green areas are rich in chlorite and muscovite mica derived from clay in the original limestone. Another popular green rock was *Marmor Thessalicum (Verde Antico* = "Ancient Green"), a breccia of serpentinite and white marble fragments in a green matrix from central Greece. Strictly speaking, this rock is not marble in the geological sense, that is metamorphosed limestone, but in antiquity, the word was used for any rock that could take a polish. A striking breccia of white marble blocks in a red matrix called *Breccia Corallina* ("Coral") was quarried about 100 kilometres southeast of Istanbul. The red colour is from small crystals of haematite. *Greco Scritto* ("Greek Writing") is a remarkable white marble with black (graphite-rich) squiggles from near Ephesus.[280] *Travertine* is a type of limestone deposited from fresh water. That seen at Ephesus was quarried near the famous white terraces deposited from hot springs at Pamukkale ("Cotton Castle"), ancient Hierapolis, 150 kilometres to the east. Finally, abundant *Misio Granito* grey granite columns were quarried near ancient Pergamon, about 200 kilometres north of Ephesus.[281]

deformation is so rapid that the rock cracks and the new fractures are filled with fresh, white calcite. The combined effect of these processes strengthens the rock and gives a vast range of colours and textures (See box 6-4: Coloured Marble and Other Decorative Stones). We appreciate and value these colours, as did the Romans.[215,254] But the Greeks were more interested in pale marbles, partly because they liked to accent their statues and temples with paint, and partly

because purer marble is easier to carve and can take more detail (see Chapter 5).[255]

The marbles and schists of the Ephesus region were formed at two different times (Figure 6-5). The older rocks that underlie Ephesus and the region just to the south consist of thin layers of grey to black marble, alternating with schist. These marble layers were good for rough construction and were extracted from many small quarries around the city. The younger marbles and schists that occur to the north and east of Ephesus are much purer, and hence paler, than the older marbles and occur in thicker layers, reflecting the original composition of the limestone precursors. The purity and thickness of the marble layers made it suitable for quality construction and indeed it was this marble that was quarried for the temple.

The metamorphic rocks around Ephesus continue to the west for over 400 kilometres, through the Cycladic Islands, to Attica and Evvia (Plate 13a). The original rocks were limestones formed in warm shallow seas rather like the current Bahamas Banks. Around low islands in this sea, weathering and erosion shed mud into the nearby waters. About fifty million years ago, large-scale plate tectonic movements forced parts of the crust deep into the earth, where temperatures of about 500°C metamorphosed the limestone to marble and the muds into schist.[256] Subsequent forces stretched the crust and allowed the blocks to rise again to the surface.

We often get the impression that marble is everywhere in the Aegean region. Although it is widespread, its presence is often overestimated because marble is resistant to erosion, and so we see it in outcrops and cliffs, whereas other rocks like schist or marl are easily weathered into soil and only exposed along the coast or in modern excavations such as along roads.

Although the ancient wonder was the marble temple, it was just an adjunct for the adoration of the goddess Artemis, whose unusual cult statues have been mentioned (see box 6-1: The Cult Figure of Artemis). We know about other aspects of her worship from the activities of a Christian missionary in the first century CE.

Paul, Artemis and Meteorites

In about 55 CE, Paul (Saul) was preaching at Ephesus and incurred the wrath of the people when he tried to convert them to a new religion, now known as Christianity. A senior city official intervened to prevent a riot and said, "Fellow Ephesians, doesn't all the world know that the city of Ephesus is the guardian of the temple of the great goddess Artemis and of her image, which fell from heaven?" (Bible: Acts of the Apostles, 19). This short passage has suggested to some people that the original cult object of Artemis was a meteorite (Figure 6-8). And it may not have been the first time that Paul encountered a natural celestial phenomenon (see box 6-5: Veneration of Fireballs).

At first glance, the association does not seem likely: the cult statues in no way resemble a meteorite (see box 6-1: The Cult Figure of Artemis) and, moreover, there is no other literary or archaeological support for the idea.[257–259] However, there is a direct theological link between Zeus, the father of Artemis, and celestial objects. His father, the Titan Cronos, had the bad habit of eating his children, so his wife substituted a stone for the infant Zeus. When Zeus had grown up, he had his revenge and forced Cronos to vomit up his children and finally the stone, which fell to earth at Delphi where it was worshipped. There are several other examples of veneration of meteorites in the ancient world.[258]

Some people have proposed another interpretation of the biblical passage: that a stony object, possibly a meteorite, was venerated alongside the Artemis statue and it may have in fact been this article in a cage-like reliquary that adorns her head in some cult images.[156] Indeed, the official who spoke to the people was a maker of small silver shrines, which may have been souvenirs of the reliquary. If this was so, then the meteorite may have had a function similar to the bones of saints and prophets venerated in younger religions, as a physical link with a deity or holy person. Unfortunately, no meteorite has been found at Ephesus or indeed any other sanctuaries in

Figure 6-8: This fresh, stony meteorite has a typical dark, smooth exterior and a paler interior. It is ten centimetres long and fell near Saint-Robert, Canada, in 1994. Photo courtesy of the author.

the Mediterranean region—this may be because most meteorites are not distinctive or impressive rocks, and may have been misplaced by priests or overlooked by early excavators.[260]

The stars are a permanent part of the sky, the domain of the gods, so when a star appears to leave, it is a powerful event, especially if a physical part of the heavens, a meteorite, descends to earth and can be recovered later. Most meteorites are fragments of asteroids, rocky bodies that orbit the sun between the planets Mars and Jupiter. When the solar system formed, 4.5 billion years ago, most material amalgamated to form rocky planets such as the earth, but in the future asteroid belt, the gravitational pull of the giant planet Jupiter disturbed the process and no larger planet could form there. This same disruptive force continues to cause asteroids to collide, making fragments, some of whose orbits may lead them to hit the earth.

Most meteorites have compositions that are very similar to earth rocks—those made of metallic iron are actually quite rare—so once it has fallen, a meteorite is just a rock unless it can be linked back to the sky by observations of the steak of light produced during its fall.[261] The latter, called a meteor, is produced by the friction of the air as the asteroid is slowed down from its speed in space, 50–200 thousand kilometres/hour, to only one to two hundred kilometres/hour when it hits the earth.[261] This process heats the fragment's surface to thousands of degrees Celsius, sending out intense light and possibly causing the asteroid to explode. Most of us have seen "shooting stars," small meteors that last for a few seconds, which are commonly produced by ice particles spalled off comets. However, the most spectacular events are the bright fireballs that take 20–40 seconds to cross the sky—these are also the most likely to deliver meteorites to the earth's surface (see box 6-5:Veneration of Fireballs).

Box 6-5 Veneration of Fireballs

For most of us, a bright fireball or even a less impressive "shooting star," is a special event, as we spend little time outside at night and streetlights make a dark sky rare, but in antiquity people would have seen such meteors quite often. In the 1st century CE, the astronomer Claudius Ptolemy explained the origin of meteors using a heliocentric model, in which the earth was surrounded by concentric spheres holding the planets, sun, and stars, and beyond was the realm of the gods. When the gods wanted to have a look at us, they peeled back the sphere of stars and may inadvertently let a few slip down to earth. At this time the gods are more receptive to our wishes as they are not screened by the sphere of the stars.

At Ephesus, a fireball or meteor may perhaps have been regarded as a sign of the goddess descending to earth. Aspects of the Artemis statue may reflect this link: in many copies of the statue the head is black, like a newly fallen meteorite and the wide collar behind her head is covered with zodiac symbols linking her to the stars.

However, this is just my speculation, as there are no records that support this idea.

There may be another connection between a fireball and events at Ephesus, again via Paul (Bible: Acts of the Apostles, chapters 9, 22, 26). In 31–36 CE he was travelling to Damascus with companions to arrest followers of "The Way," as early Christians were known, when he saw a flash of light that temporally blinded him, accompanied by sounds that he interpreted as words in Hebrew. This event converted him from an opponent of Christianity to its greatest supporter. The Christian interpretation is that this was Jesus talking to Paul, but it may have been a geomyth. It is possible that the event was a fireball, not dissimilar to the impressive fireball and explosion at Chelyabinsk, Russia, in 2013.[282] Such events are so short that you have to be looking in the right direction at the right time. They can also induce temporary blindness. And as for the words in Hebrew, we know that fireballs can produce simultaneous sounds—radio waves created in the upper atmosphere by the hot plasma are received by nearby conductors, such as pieces of metal, which resonate and make noises. If a large fireball like this was indeed what Paul experienced, it could have delivered meteorites but they would have fallen a hundred kilometres or more from him and would not have been associated with the event.

There is a coincidental link between mythology and cosmology in the story told by Paul: the city official at Ephesus talked of an image that "fell from heaven," but the Greek word that he used, "diopetes," can also be translated as "fell from Zeus," and Zeus was equated with the Roman god Jupiter. Jupiter-Zeus was the most powerful of the gods and regularly disrupted the lives of his lesser colleagues, in the same way as the planet Jupiter perturbs the orbits of the asteroids.

Although the events triggered by the visit of Saint Paul in 55 CE was a harbinger of the end of the temple, the cult of Artemis and the city grew in importance for several hundred years—at its peak, Ephesus may have been the second-largest city in the Roman Empire. During this period,

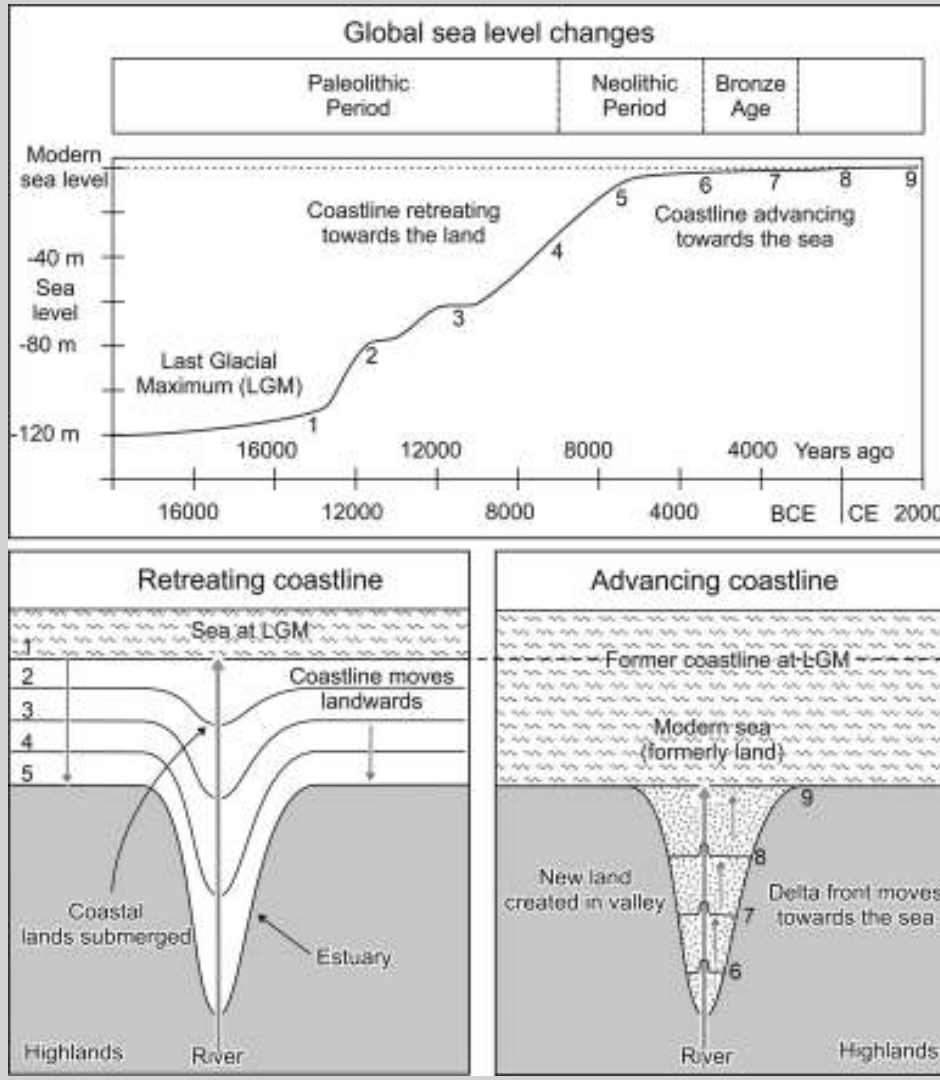
the development of the community was closely linked to the changing geography of the Cayster Valley, itself a product of global climatic events.

Evolution of the Gulf of Cayster

We commonly suppose that without human intervention the natural landscape is relatively constant, but that is not always the case, especially in recent times, when the earth is still adjusting to the end of the last glacial epoch. Twenty thousand years ago, parts of North America, Europe, and Asia were covered by up to three kilometres of ice, as were the mountains in central Turkey. Although there was no ice near Ephesus, the distant glaciers had their effects there—water that was frozen on the continents ultimately came from the oceans, whose level dropped by 120 metres, drastically changing the coastline by linking islands to each other and the mainland. The landscape was also affected: river beds became steeper and erosion cut canyons far into the continent. The hillsides on either side of the valleys were also strongly incised with smaller canyons. The geography changed again as the ice sheets melted and sea level rose, stabilizing near its current height seven thousand years ago (see box 6-6: Sea Level and Cultural Developments**)**. Islands were again isolated from the mainland and large, shallow estuaries formed as valleys were flooded. Initially, there was little vegetation on the hills and erosion charged the rivers with sand and mud, which were deposited in the bays, but this process slowed down as forests became established in the hinterland. The deltas of these rivers did not have the classical triangular shape of those exposed to waves, like that of the Nile (see Chapter 8), but a shape described as "birds-foot" where the distributary channels of the river deposited sediments into calm waters such as those of the Cayster Gulf (Figure 6-9).

In the Cayster Valley, the post-glacial canyon probably extended to Belevi, 15 kilometres from the current coast (Figure 6-5, Figure 6-9).[262–265] Although the delta immediately started to advance into

Box 6-6 Sea Level and Cultural Developments



Sea level variations may have had a major impact on cultural development. Image by author after Fleming, K., et al., 1998, Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth and Planetary Science Letters* 163(1): 327–342.

Since the coldest glacial period (Last Glacial Maximum), twenty thousand years ago, there has been a huge rise in sea level caused by the melting of continental glaciers and subsequent refilling of the oceans.[283] Sea level rise started to become important about fifteen thousand years ago and continued until seven thousand years ago when it stabilized close to its current level. As sea level rose, the coastline moved further inland by up to tens of metres per year.

Since that time, significant sea level changes were caused by land movements during earthquakes (see Chapter 7: Earthquakes).

Major changes in the landscape accompanied rising sea levels. The most fertile and valued land was adjacent to the sea, in river valleys and deltas, hence retreating coastlines must have forced communities inland where they came into conflict with existing populations. We know little about these coastal communities and their troubles as the remains are now deeply submerged but inland sites commonly testify to the violent nature of Paleolithic and Neolithic society.[284]

Stabilization of sea level initiated major changes in the landscape: the coastlines advanced rapidly as rivers deposited sediments eroded from the hinterland into the shallow waters of the estuaries, thus rapidly expanding the amount of fertile arable land. This reduction of population pressure and conflict may have ultimately led to cultural developments first expressed by the use of copper in the late Neolithic Period and later on by use of the harder metals bronze and steel.

Today, we are in another period of arable land loss. So far, except in river deltas, the effect of sea level rise has been relatively unimportant but will become much more significant in the coming decades with implications in both rural and urban settings.

the gulf, by the time of the first settlements at Ephesus there was still a large bay that provided a sheltered anchorage, and the newly formed flood plain of the river was agriculturally productive. New communities flourished and, by the 8th century BCE, had established an important sanctuary at the eastern end of the bay.[264] However, the growth of the population in the hinterland led to renewed soil erosion—grazing animals removed vegetation and kicked sediments into the rivers, and ploughing exposed the soil to winter rains—so that the delta then advanced into the shallow waters of the gulf even more rapidly than before. As the bay was filled in by sediments, the region's inhabitants coped by moving the harbour and centre of settlement progressively eastwards. The earliest sacred harbour, just north of the Temple of Artemis, was the first to be lost, followed by

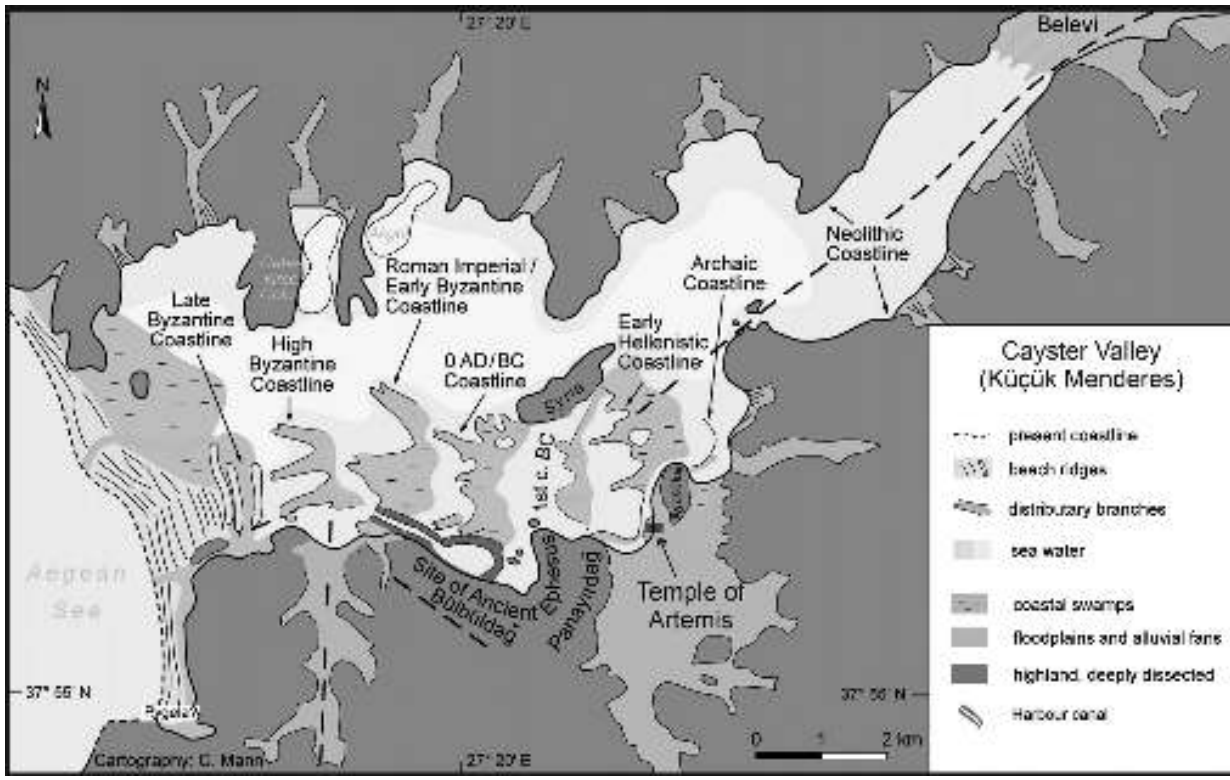


Figure 6-9: The delta of the Cayster River (now Küçük Menderes) has advanced steadily from near Belevi in Neolithic times (about 5000 BCE) to its current position along the coast. Image by author after Stock, F. et al., 2013, "In search of the Harbours: New Evidence of Late Roman and Byzantine Harbours of Ephesus." *Quaternary International* 312: 57–69.

a commercial harbour west of the sanctuary, which was filled in not only by sediments from the Cayster River but also the Selinus and Marnas Streams (Figure 6-5).

In 287 BCE, Lysimachus, a successor of Alexander the Great, started construction of the Great Harbour (Figure 6-9, Plate 12a). It was part of an ambitious plan that included the construction of a new city surrounded by strong walls. There are stories that the inhabitants of the old town east of the temple would not move, so Lysimachus blocked the drains during a storm and flooded them out. The harbour was built in slightly deeper water beside Mount Pion (now Panayırdağ) and was initially a great success. However, sediments from the Cayster River soon started to spill into the harbour. In the 2nd century BCE, a breakwater was constructed to keep out the sediments, but it failed as fine silt then accumulated in the enclosed harbour basin and was

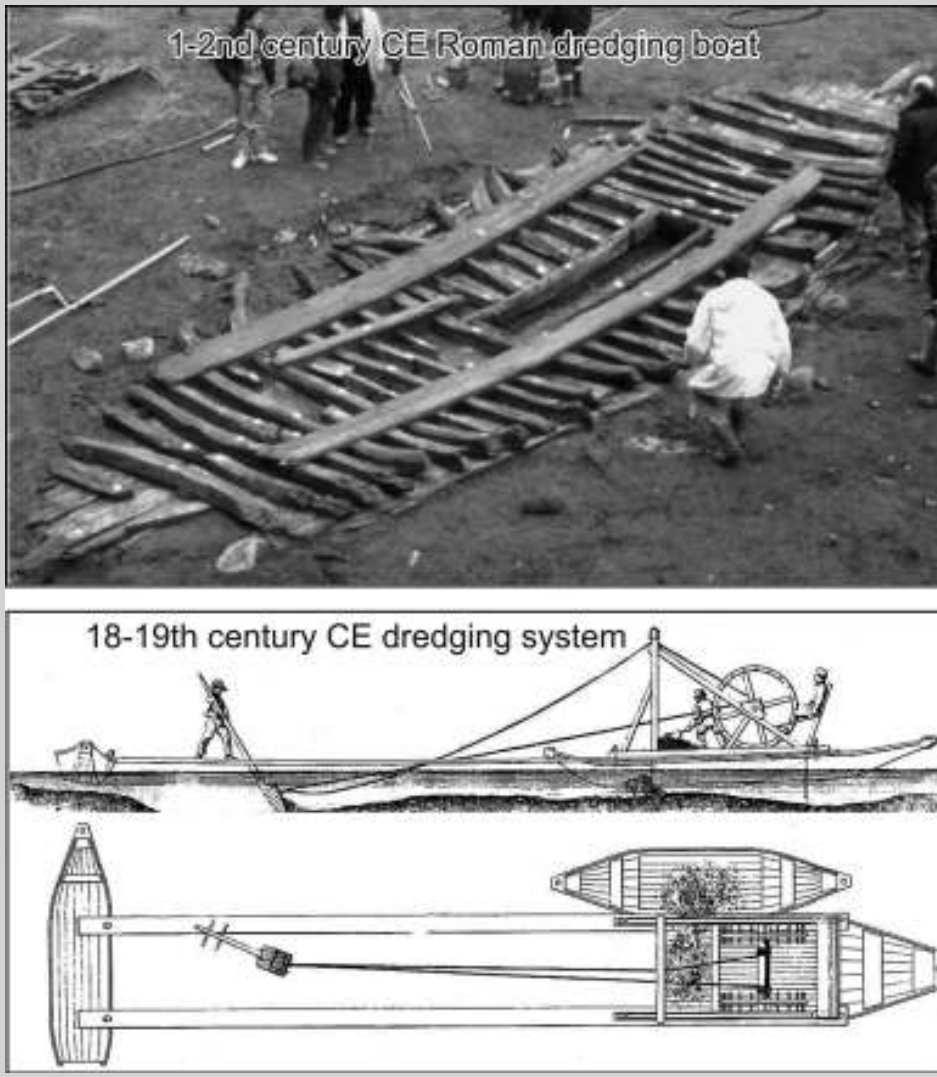
not removed by currents produced by river flow or tidal action. Later the breakwater was extended, further narrowing the mouth of the harbour and compounding the problem. As if this was not sufficient, construction debris and damaged trade goods were dumped into the harbour. Dredging under the Greek and Roman regimes helped keep the harbour open to the sea but the advance of the Cayster delta soon necessitated a canal (see box 6-7: Dredging Techniques). This situation could not continue indefinitely and by Byzantine times (5th–13th centuries CE), Ephesus had been reduced to a village: the struggle against natural forces had been lost, and all that remains now of the harbour is a swampy lagoon.[266]

I've talked about how the Cayster delta advanced by deposition of sediments but there is another phenomenon that may have been important: tectonic movements during earthquakes. This process played an important role in the history of the Colossus (see Chapter 7), and may have been important here also. This region was and is tectonically very active (see box 6-3: The Aegean Coast of Turkey) and geologically recent fault movements were made visible by disruption of a Roman aqueduct (see box 6-8: The "Ghost" Earthquake of 178 CE). A nearby earthquake in 2020 CE shows us that the region is still tectonically active[267] when an east-west fault north of Samos and west of Ephesus moved 1.8 metres, causing 10–30 centimetres uplift of the island and adjacent parts of the mainland (see box 6-3: The Aegean Coast of Turkey). Similar uplift movements in the past may have enhanced the advance of the Cayster delta by exposing shallow banks of sediments. So much for the harbour—what now of the history of the city?

Roman Ephesus

The wealth of Ephesus reached its apogee in Roman times when the city was one of the most important commercial centres in the eastern Mediterranean. This is well illustrated by rich public and

Box 6-7 Dredging Techniques



Ancient dredging techniques. Image by author after Morhange, C. and N. Marriner, 2010, Mind the (stratigraphic) gap: Roman dredging in ancient Mediterranean harbours. *Bollettino di Archeologia online* 1: 23–32.

Dredging was necessary to keep harbours, canals, and rivers deep enough for boats to pass. Water depth was reduced by changes in the height of the land following earthquakes and the accumulation of silt, as well as by dumping of trash, a problem that has not changed with the ages.

There are no ancient descriptions of how it was done, but a 16-metre-long Roman ship excavated at Marseille had a central opening 2.5 by 0.5 metres that could have held a tool like a giant spoon for extracting muck.[285] At Naples, there are curved scour marks on the floor of the ancient harbour that must have been made during dredging by a different technique. One possibility is shown by methods used for cleaning out rivers in more recent times. Here, a large scoop is guided by a worker while another worker hauls it sideways with a boat-mounted treadmill.

private buildings in the centre of the city as well as the aqueducts that brought water to its vast population.[248,268] Although many people think of ancient aqueducts as the magnificent bridges (Figure 6-10) and fountains[269] of Roman times, water was for the most part conveyed along hillsides in pipes or stone troughs lined with lime-based cement (Figure 6-10). Such constructions were more vulnerable to pillaging for materials and so the exact route of these extensive engineering structures is not always clear.

The earliest aqueduct dates from the 6th century BCE and may have been built to supply water to a basin in front of the Altar Court after the sacred spring had run dry. The aqueduct carried water from springs 7 kilometres to the east of the temple at Şirince, one of the sources of the Silenus Stream (Figure 6-5; Figure 6-6, Plate 12b). This water source was preferred because it flowed all year, unlike the section of the stream near the temple that dried up in the summer. The Şirince springs debouche at an elevation of 500 metres and were tapped by galleries excavated into marble that overlay a layer of impermeable schist. All of the springs in the region have a similar geological origin from flow of rainwater through fissures in marble (see Chapter 4). Water was conveyed in clay pipes set in the earth until the aqueduct reached a fountain in sanctuary of Artemis, where substantial lead pipes were used, for no discernible reason. The aqueduct was remodelled many times and finally diverted to the Byzantine city of Ayasoluk in the 6th century CE (Figure 6-10).

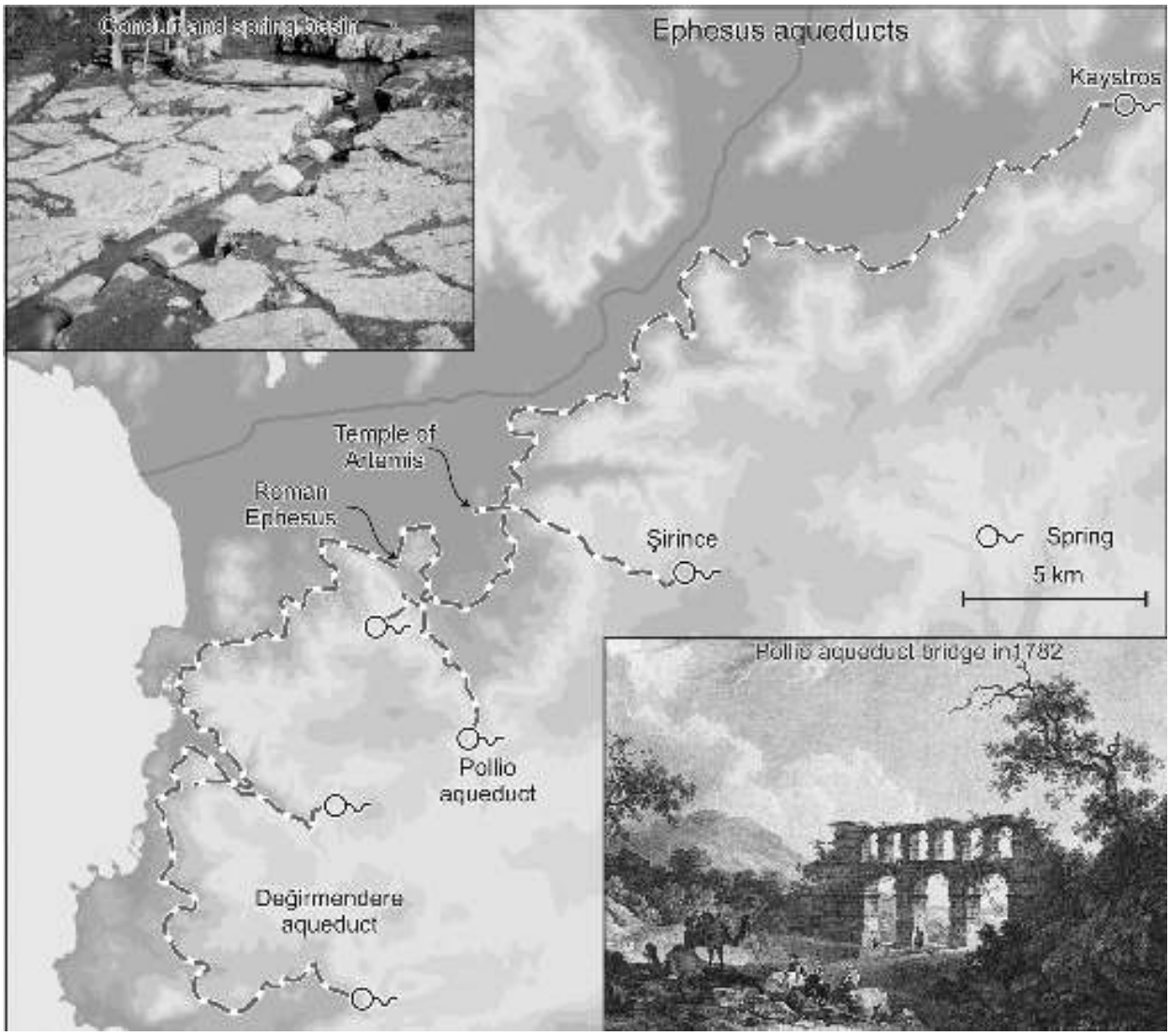


Figure 6-10: Aqueducts near Ephesus were built or rebuilt from the sixth century BCE until Byzantine times. An early aqueduct may have delivered water from a spring at Şirince to the basin in front of the Temple of Artemis finishing in a lead and stone conduit. The Pollio aqueduct crossed the Marnas stream on a magnificent bridge. Map by author after Wiplinger, G., 2019, De Aquaeductu Urbis Ephesi. Water for Roman Ephesus. 13th Babesch Lecture, The Babesch Foundation; Inset images © Jean-Baptiste Hilair, 1782, Welcome Collection, CC BY 4.0 and Kerschner, M., 2015, Der Ursprung des Artemisions von Ephesos als Naturheiligtum. Naturmale als kultische Bezugspunkte in den großen Heiligtümern Ioniens. K. Sporn, S. Ladstätter, M. Kerschner (eds), Natur–Kult–Raum. Akten des internationalen Kolloquiums, Wien: 187-243.

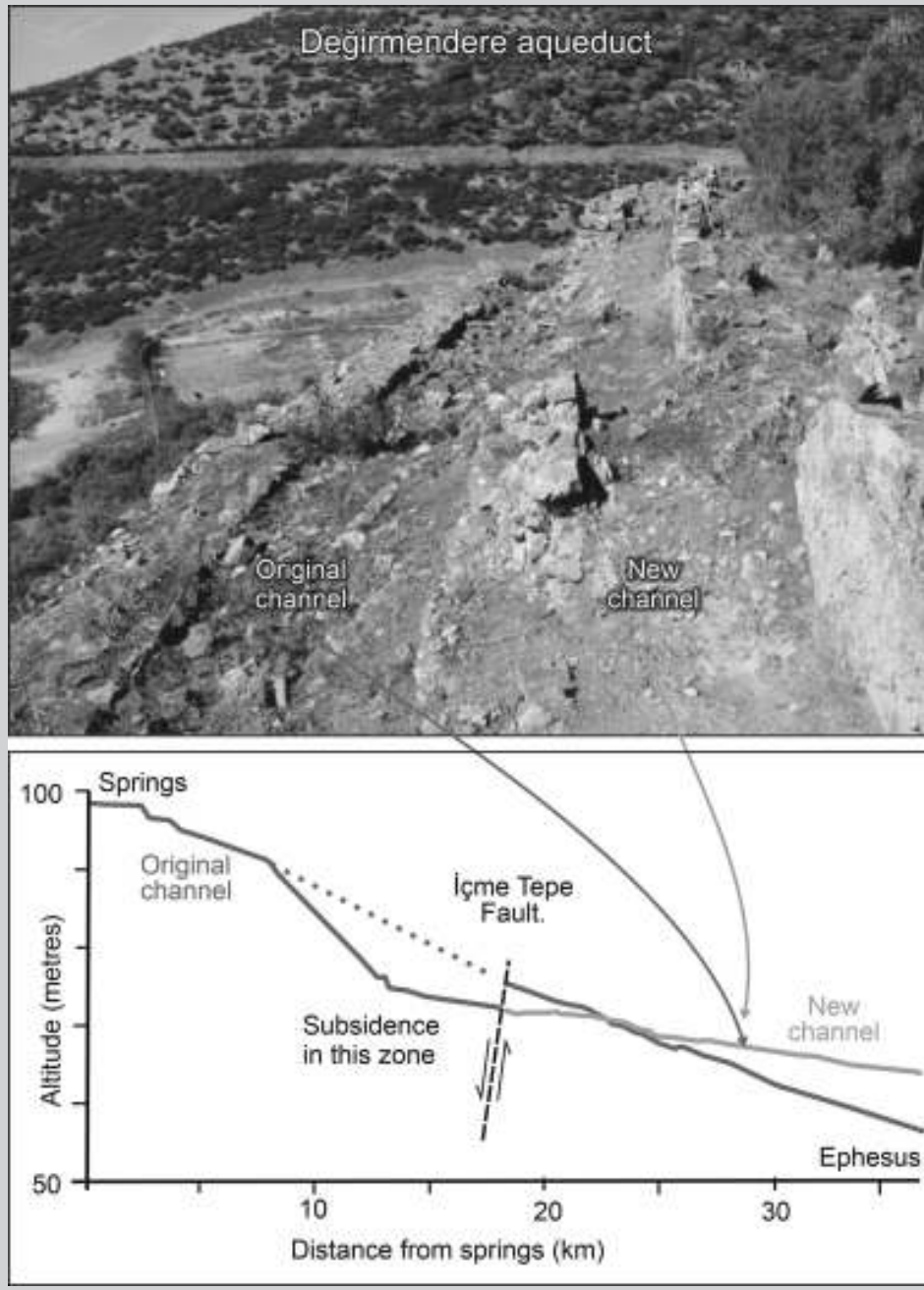
The new city that Lysimachus built in the 3rd century BCE needed its own water supply. At first, a spring near the city was tapped but soon the Pollio aqueduct was extended to tap another perennial spring 7 kilometres to the east, which was a source of the Marnas Stream. The spring here may be associated with the Ephesus Fault, which ran through the city (Figure 6-5). Water was conveyed in clay pipes along the hillsides and over a stream on an elegant stone bridge (Figure 6-10).

Ephesus thrived during Roman times from trade and pilgrims to the temple, as testified by the magnificent remains of the city. A population of perhaps two hundred thousand people needed enormous amounts of water for drinking and washing. The first Roman aqueduct tapped perennial springs far upstream near Kaystros and transported the water mostly in a masonry trough some 38 kilometres to the city. Flow in an open channel instead of pipes introduced a new problem, the accumulation of "sinter" on the walls. This happened because the spring water was charged with carbonate from its flow through marble. As it flowed, carbon dioxide gas was lost to the atmosphere resulting in the precipitation of carbonate minerals on the channel walls, in a way similar to the formation of stalactites in caves or scale in a kettle. This sinter accumulated in layers and could completely fill an aqueduct channel, necessitating costly repairs. The flow of this aqueduct eventually became inadequate and the Değirmendere aqueduct was built to tap perennial springs in the hills 12 kilometres due south of the city. Up to 700 cubic metres of water per day was transported in a trough, through tunnels and over bridges to the city. A major earthquake in 178 CE broke this aqueduct and must have caused serious damage to the town, but if it affected the temple then repairs were done (see box 6-8: The "Ghost" Earthquake of 178 CE).

The Demise and Burial of the Temple

The fortunes of the temple and the city seem to have turned in 262 CE, but the exact nature of the event is unclear.[270] It is known that many of the larger public and private buildings of the city were damaged

Box 6-8 The "Ghost" Earthquake of 178 CE



Disruption and rebuilding of a Roman aqueduct. Image by author after Passchier, C.W., et al., 2013, Normal fault displacement dislocating a Roman aqueduct of Ephesos, western Turkey. *Terra Nova* 25(4): 292–297.

Although a powerful earthquake in 178 CE must have disrupted life considerably in Roman Ephesus, nobody seems to have described it and we only know about it from the breakage and rebuilding of the

important Değirmendere aqueduct that fed water to Ephesus from springs to the south.[286] Like other Roman aqueducts, this was built with great engineering skill: its original slope was constant at about 1 metre per kilometre. The aqueduct was disrupted by three metres of vertical movement where it crosses the major Içme Tepe Fault 5 km south of Ephesus. This huge displacement must have occurred during a magnitude 6 to 7 earthquake. We can estimate the time interval from the aqueduct's construction to its disruption from the accumulation of "sinter" in the old channel: this corresponds to thirty to thirty-five years of use, agreeing with other evidence for an earthquake in 178 CE. An event of this magnitude and proximity would have destroyed many houses in Ephesus, which would not have been very resistant to earthquake movements. However, the construction of the temple incorporated several anti-seismic precautions so it does not seem to have been damaged significantly. North of the fault, the aqueduct was rebuilt at a different level, testifying to the continuing vigour of the city, and the thickness of the sinter shows that it was used for two hundred years afterwards. The current topography of the aqueduct shows that there have not been any major earth movements along this fault since the 178 CE event, which must comfort the inhabitants of the modern coastal city of Kuşadası through which the route of the ancient aqueduct now passes. However, there is a 45-metre-high scarp on the Içme Tepe fault near the coast, showing that it has been very active in the geologically recent past and will undoubtably move again with catastrophic results for the community unless building codes are strictly enforced.

The only Roman record may be a tablet, now in the British Museum, put up by a junior official at Ephesus, "on account of his own merit," possibly in dealing with the destructive effects of the earthquake. The event may also have been recorded obliquely in the "Acts of John," an early Christian manuscript that was not included in the Bible. In this document, it is mentioned that John the Apostle was praying at the Temple of Artemis, trying to exorcise its demons, when "of a sudden the altar split in many pieces . . . and half the temple fell down."[287] John was active in the first century CE but the manuscript first circulated in the second century and this account may have been added at that time.

or destroyed late in the 3rd century, as was the temple.[271] Some authors link this to an earthquake mentioned in the 4th–5th century CE *Historia Augusta*, but this source is notoriously unreliable. In the entry for 262 CE, an earthquake in Asia Minor is briefly described and mention is made that it affected the whole Mediterranean region, which would have been possible if the earthquake produced a significant tsunami, but there is no record of this. It is more likely that several different events were conflated as this was a time of political turmoil and communications were difficult. We know that the Değirmendere aqueduct was not disrupted at this time, casting doubt on the whole idea of a nearby earthquake (see box 6-8: The "Ghost" Earthquake of 178 CE), although a distant, more powerful earthquake cannot be discounted. There is, however, more likely explanation involving human intervention.

The Goths, a people from eastern Germany, invaded the region in this same year and sacked the temple and city. The temple was certainly a tempting target as it was full of valuable religious objects as well as being the treasury for the city and much of Asia Minor. The Goths soon withdrew, but the temple was never repaired and, as usual, the site became a convenient quarry. There is a legend that some of the columns were incorporated into Hagia Sofia ("Holy Wisdom"), the great church of Emperor Justinian in Constantinople (Istanbul), which was completed in 537 CE. A more likely use was for the construction of the 6th-century Basilica of Saint John a few hundred metres to the northeast and later the 14th-century Isa Bey mosque, which overlooks the ruins of the temple (Figure 6-5). In 401 CE, a visit by the Patriarch (Archbishop) of Constantinople suggests that Christianity had officially supplanted the worship of the old gods. Finally, in the 6th century, a church dedicated to Saint Mary was built in the inner courtyard of the temple ruins, completing the transfer of power from a mother-goddess to the mother of a god.[272]

Over the next 1,300 years, sediments deposited by the Marnas and Selinus Streams completely covered the site (Figure 6-11). In the 1860s, an English architect, John Wood, spent ten years digging test

Figure 6-11: John Wood's excavation team dug through six metres of river sediments to reach the remains of the temple. A section of these sediments is still visible towards the back of the excavations. Today, the ruins are waterlogged for much of the year, and the only sense of scale is given by a badly reassembled column. The Isa Bey mosque overlooks the ruins. Photo by author and image from Wood, J.T., 1877, "Discoveries at Ephesus, Including the Site and Remains of the Great Temple of Diana." Longmans, Green and Co, London.

pits at random throughout the plain east of the Roman City but without success.[237] He finally found an inscription that directed him to follow the Sacred Way from the Magnesian Gate in the south of the city (Figure 6-6). Once he found the start of the Sacred Way, it was easy to follow, as it was a monumental structure, 12 metres wide and paved with marble. The road went northwards along the base of the hill and then turned eastwards to the precinct wall and onwards to the temple itself. Nowadays, such a buried structure would have been located more easily with geophysical surveys (see box 6-9: Non-destructive Surveys), although excavation would have been necessary to confirm its identity.

Initially, the excavators were rather disappointed as most of the larger marble fragments had already been removed, but the remaining finds were nonetheless sent to the British Museum, including a spectacular column base (Figure 6-4). Since that time, careful excavation has revealed many aspects of the temple, its cult and city, and continues to the present day. As for the excavation pit, it is now filled with water most of the year because the land has sunk and the water table has risen since antiquity (Figure 6-11). The lone standing column was

Box 6-9 Non-destructive Surveys

The laborious survey methods used by archaeologists in the 19th century are now complemented by non-destructive geophysical methods.[288] These were developed locating mineral deposits, oil and water reserves, and the characterization of engineering sites, and they have been adapted for use by archaeologists. They are commonly used to locate the best sites for excavation.

One of the most popular and rapid surveys uses a portable magnetometer to measure the characteristics of the earth's natural magnetic field. This global field is produced in the core of the earth and modulated by the mineral magnetite (Fe_3O_4) in rocks and soils near the surface. The resolution is good enough that walls and trenches less than a metre across can be located.

Another popular method is Ground-Penetration Radar (GPR), which uses high-frequency electromagnetic (radio) waves to map the subsurface. It actually responds to amount of water retained in the soil, which is commonly changed by construction and other activities. This same parameter is also determined by measuring the electric resistance of the ground using electrodes and currents, or electromagnetic coils. Both methods produce two-dimensional slices through the site that can be assembled into three-dimensional surveys. A minor drawback of all these methods is they cannot generally "see" structures under the water table, so they are best used in the dry season.

re-erected in the 19th century from fragments of different columns and is not a good reconstruction. Few of the thousands of visitors to the magnificent ruins of Roman Ephesus bother to visit this desolate place, once the site of the most impressive temple of the ancient world. If you do get the chance to see this part of the world, then I would suggest a detour to Didyma, 60 kilometres to the south, where a similar temple is much better preserved.

7

The Colossus of Rhodes

The Colossus

The wondrous bronze statue at Rhodes was not only a memorial to an important victory but also a tower to guide boats into the harbour and a reminder to neighbouring states of the power of the city (Figure 7-1). Above all, it represented the sun god Helios, the patron of Rhodes. Like the other ancient wonders, it was exceptional: the biggest bronze statue at that time. And it stood out in other ways too: the metal from which it was cast came from the largest copper deposit known at the time, and it was finally toppled by one of the largest earthquakes in this region. All that survives now is a name: Colossus, which still invokes the scale and power of the statue.

Rhodes is a fertile, sunny island first inhabited about ten thousand years ago, soon after the climate warmed up following the last glacial period. The Minoan people arrived in the 17th century BCE followed by the Mycenaean Greeks, in about 1450 BCE. The geographer Strabo, writing in about 17–23 CE, relates that "In earlier times Rhodes was named . . . Telchinis after the Telkhines [offspring of the gods], who took up their abode in the island. Some say that the Telkhines were maligners and sorcerers, who poured the water of the Styx [the river in Hades], mixed with sulphur, upon animals and plants to destroy them. But others, on the contrary, say that since they excelled in workmanship, they were maligned by rival workmen and

Figure 7-1: In 282 BCE, a 33-metre high bronze statue of the sun god Helios was completed in Rhodes. We have no ancient images of the Colossus, except possibly the head, so to reconstruct it we must use meagre ancient descriptions and other statues created at that time. It may have resembled this 3.4-metre-high statue of Helios by Johannes Benk from the dome of the Naturhistorisches Museum, Vienna. Photo modified by author after © Hubertl / Wikimedia Commons, CC BY-SA 4.0.

thus received their bad reputation; and that they first came from Crete to Cyprus, and then to Rhodes; and that they were the first to work iron and bronze, and in fact fabricated the scythe for Cronus [the Titan]." (14.2.7; www.theoi.com). So even at this time, the island of Rhodes had a reputation for skilled, if semi-divine, metalworkers. The link with the island of Cyprus is interesting, as it was an important source of copper, the major ingredient of bronze, throughout much of antiquity. In addition, there is an allusion to the sulphurous pollution produced during the processing of sulphide copper ores.

The Dorian Greeks arrived in the 9th century BCE, with their own myths: the poet Pindar related that the island arose from the sea to become the domain of Helios and his consort, the sea nymph Rhode. Could this be a geomyth developed from early observations of geological uplift? The fertility of its soils and favourable climate made the island prosper. Its location on major trade routes became more important after the start of construction of the new city of Rhodes and its five harbours in 408 BCE. From then on, the prestige and power of the navy, commanded ably by an aristocratic clan, assured safe passage for cargo boats from Aegean and Egypt, making Rhodes the most important entrepot in the region.[289] The standing of the city was at its height in 282 BCE, when the huge bronze statue of the god Helios, the Colossus of Rhodes, was completed.

The story of the Colossus has been told many times, but briefly, it starts with the death of Alexander the Great in 323 BCE.[290] His short-lived empire was split amongst his friends and generals who immediately started quarrelling. The island allied itself with Ptolemy, who controlled Egypt, against the powerful Antigonus who controlled Asia with the aid of Alexander's gold treasure and the bulk of his army. In 307 BCE, Antigonus asked the Rhodian to side with him against Ptolemy but they refused as they had a good trading relationship with Egypt. Finally, in 305 BCE, Demetrius, the son of Antigonus, attacked Rhodes. Ptolemy sent reinforcements from Alexandria to enhance and protect his region of influence. Together, the Rhodians and Egyptians forced Demetrius to abandon his siege and retreat. He left behind his

war machines, including a siege tower 50 metres high covered in iron plates. The people of Rhodes sold some of the material to finance the construction of the statue of Helios to commemorate their victory. They probably also recycled some of the wood, bronze, and iron from the tower into the new statue.

Chares of Lindos, a pupil of the famous sculptor Lysippos, designed the statue, which was built between 294 and 282 BCE. We do not know what the Colossus looked like, as no images or copies have survived, but the head may have resembled the images on the coins from Rhodes (Figure 7-2), which may be in turn have been inspired

Figure 7-2: The head of the sun god Helios adorned many coins from Rhodes, such as this silver two-drachma piece (304-167 BCE). Photo ©Marie-Lan Nguyen / Wikimedia Commons, CC BY-SA 4.0.

by statues of Alexander the Great. Indeed, the only official sculptor of Alexander was the same Lysippos who taught Chares.

There are only three surviving descriptions of the statue—by Strabo (64 BCE–24 CE), Pliny the Elder (23–79 CE) and Philo of Byzantium (280–220 BCE or perhaps much later)—but there are few details. It is unlikely that any of them actually saw the statue, intact or fallen. The longest description by far is that of Philo, but it deals mostly with the construction methods, which is in keeping with his other works on engineering.[290]

"At Rhodes was set up a Colossus of seventy cubits high [33 metres], representing the Sun; for the appearance of the God was known only to his descendants. The artist expended bronze on it as seemed likely to create a dearth in the mines: for the casting of the statue was an operation in which the bronze industry of the whole world was concerned. . . . The artist fortified the bronze from within by means of an iron framework and squared blocks of stone, whose tie-bars bear witness to hammering of Cyclopean force. Indeed, the hidden part of the labour is greater than the visible. . . . Having built a base of white marble, the artist first fixed upon it the feet of the Colossus up to the height of the ankle joints, having worked out the proportions suitable to a divine image destined to stand to a height of seventy cubits [33 metres]; for the sole of the foot already exceeded in length the height of other statues. For this reason, it was impossible to hoist up the rest of the statue and place it upon the feet, but the ankles had to be cast upon the feet and, as when a house is built, the whole work had to rise upon itself. And for this reason, while other statues are first modelled, then dismembered for casting in parts, and finally recomposed and erected, in this case, after the first part had been cast, the second was modelled upon it, and for the following part again the same method of working was adopted. For the individual metal sections could not be moved. After the casting of the new course upon that part of the work already completed, the spacing of the horizontal tie-bars and the joints of the framework were looked to, and the stability of the stone blocks placed within the figure was ensured. In order to advance

the project on a firm basis throughout, the artist heaped up a huge mound of earth around each section as soon as it was completed, thus burying the finished work under the accumulated earth, and carrying out the casting of the next part on the level. So, going up bit by bit, he reached the goal of his endeavour, and at the expense of 500 talents [15 tons; see box 8-1: Ancient Units of Length, Distance and Weight] of bronze and 300 talents [9 tons] of iron he created, with incredible boldness, a god similar to the real God; for he gave a second Sun to the world."

This construction method is possible but unlikely. I say this because a 15-metre high statue of Buddha at Nara (Japan) that was finished in 757 CE using a similar method needed 500 tons of bronze and a workforce of eight thousand people, which represented considerably more resources than were available to the Rhodians.[291] No evidence for casting in courses in the 3rd century BCE Greece survives and it is unclear why Philo wrote about this idea in so much detail. Maybe it was the product of a personal "thought experiment" or just ignorance as to how statues were commonly made. It is much more likely that the Colossus was made using the "lost wax process," which we know was used for other monumental statues, albeit on a somewhat smaller scale.[292,293]

We do not know how the statue was built, but the following plan is a possible approach. The first stage was to excavate down to bedrock and build a base of stone blocks securely linked to resist earthquakes. An iron frame was set into this construction to hold the statue. Onto this framework, a full-size model of the statue was made using wooden beams smoothed with plaster, similar to the method used for the statue of Zeus at Olympia[291] (see Chapter 4). Sections of the statue were cast using this model.

First, the edges of the new section were laid out on the model. Some edges would have been on the already cast sections beside and below the new section while other edges may have followed lines in the statue. Wax was then applied to this part of the model until it was sufficiently thick and strong to be removed in one piece. More wax

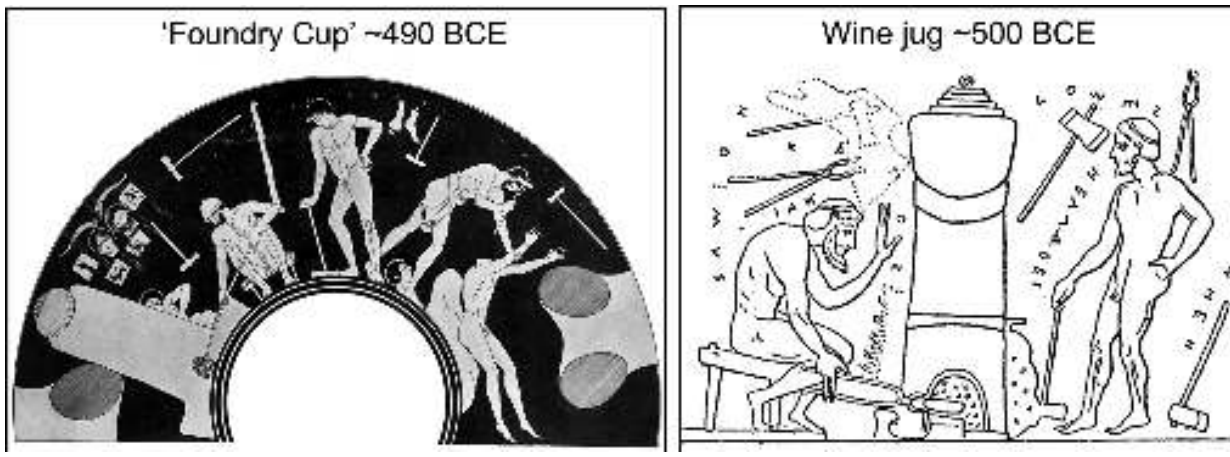


Figure 7-3: Metalworkers are shown here on two ceramic pots. On the left, a seated worker draws molten metal from a shaft furnace. A figure partly hidden by the furnace works the bellows. Wax or ceramic models are shown in the background, hanging on a wall. Another worker finishes or cleans a partly finished statue. On the right, a worker heats a metal object in a furnace, protecting his face from the heat with his hand. The hammers suggest that it is iron being readied for smithing. In reality, the workers must have been protected by leather aprons. Image by author after Furtwängler, A. and K. Reichhold, 1910, Griechische Vasenmalerei III; Blumner, H., 1887, *Technologie und Terminologie der Gewerbe und Kunste bei Griechen und Romern*. B.G. Teubner: Leipzig.

was added to the form to make the pouring tubes, and the whole ensemble was covered with a thick layer of clay. This was first heated gently to melt the valuable wax, which was collected, and then fired to make a hollow ceramic mould that was then filled with molten bronze (Figure 7-3).[294,295] Finally, the mould was broken and extraneous parts of the casting were removed. Some sections may have been as large as 7 × 3.2 metres, the size of a casting pit from Athens of that period. A casting of this size 5 mm thick would have weighed 10 tons, giving a total weight of about 140 tons for the whole statue. At this time, it was difficult to weld bronze castings, so it is likely that bronze pins were used to join pieces together and to the iron framework, which had already been stripped of the wood and plaster model in that area. The statue would have risen as the bronze panels were added sequentially to the framework, perhaps inspiring the construction method described by Philo.

The statue must have been built within scaffolding for manipulation of the heavy components and undercover for protection from

the weather. One possibility is that parts of the frame and covering of Demetrius's siege tower were re-erected on the stone base that was to host the statue. In this case, the height of the original tower may have limited the maximum size of the statue.

We can recreate an image of the statue from these ancient descriptions, ancient coins, smaller statues of the period, and knowledge of technology available at that time. The consensus is that the statue was a rather austere image of the god, standing naked on a stone base with his feet together, perhaps holding a spear for stability and possibly a torch above his head (Figure 7-1).[290,296]

The Colossus did not straddle the harbour entrance as in the iconic image published in 1530 CE by Maerten van Heemskerck, which was just a product of his fantastical imagination.[297] A statue built in this way could have only admitted very small boats and was technically impossible at that time. Unfortunately, this image of the Colossus still persists in popular culture perhaps because it so clearly expresses power.

There are many theories as to where the Colossus stood, but none has been verified by recent archaeological excavations (Figure 7-4). One of the most popular is that it stood on a breakwater projecting into the harbour, near where Fort Saint Nicolas, a small castle built by the crusaders, now stands. It certainly makes sense to put a monumental statue near the harbour to guide, welcome, and impress visitors, just as today's Statue of Liberty does in New York. Numerous curved blocks of marble now incorporated into the structure of the crusader's fort could have been part of a circular base, which the people of Rhodes seemed to favour for their statues.[296] A weakness of this idea is that the statue is most likely to have collapsed into the water, where its remains would not have been easily accessible in antiquity for restoration or looting. In addition, we would also expect to be able to find bronze fragments in this general area, which we do not. If the Colossus was not at the entrance to the harbour, then where else might it have stood?

Statues of gods were commonly placed in the sanctuary of their temples, meaning that the Colossus may have stood next to a sanctuary

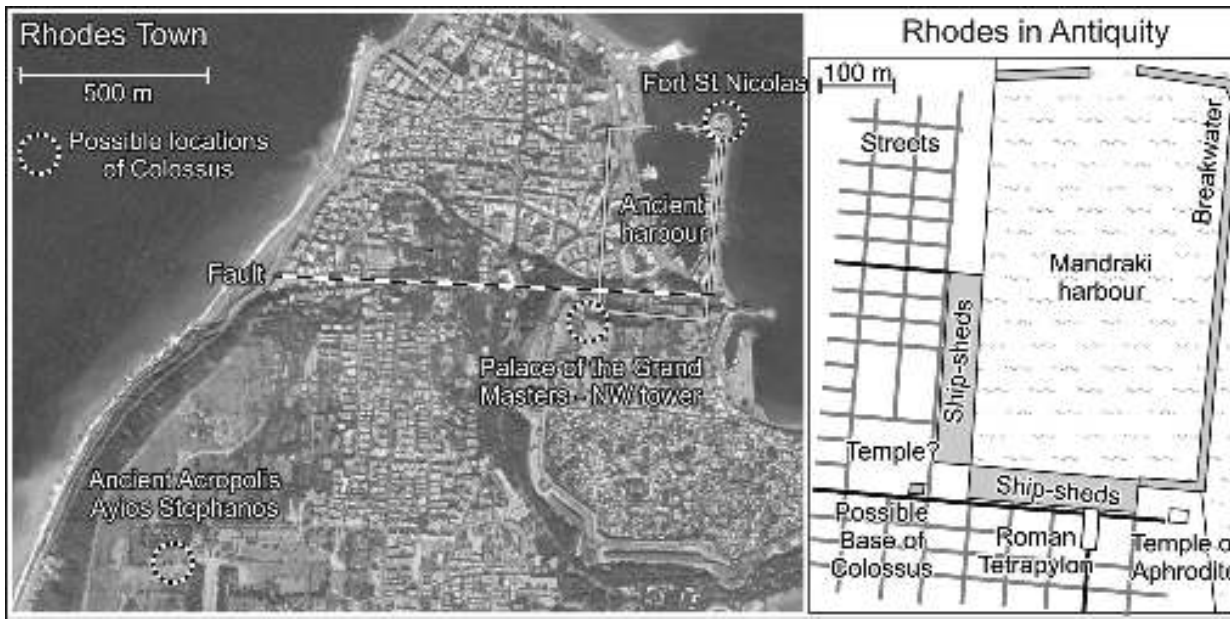


Figure 7-4: Many features of the ancient town of Rhodes are still visible today. A breakwater protected the military harbour, which was lined on the landward side by covered sheds for storing warships. Many consider that the Colossus stood on the corner of the breakwater, where Fort Saint Nicolas stands today (circle). However, it is more likely that it was on Ayios Stephanos, the ancient acropolis or where the medieval Palace of the Grand Masters now stands. Image by author after Google Earth; Blackman, D.J., P. Knoblauch, and A. Yiannikouri, 1996, Die Schiffshäuser am Mandrakihafen in Rhodos. Archäologischer Anzeiger. 1996: 371-426; Hoepfner, W.S.E.-L., 1994, Haus und Stadt im klassischen Griechenland: [Neubearbeitung]. Deutscher Kunstverl, Munchen.

dedicated to Helios, but where was this? One possibility is that it was on the acropolis, west of the modern city (Figure 7-4). On this low hill (Ayios Stephanos, 110 metres), there are the remains of a temple usually thought to have been dedicated to Apollo, but it could have been a temple of Helios, who shared many aspects of the senior god.[291,302] Ruins just southeast of the temple may be the remains of the base of the statue.

Another idea is that the Colossus stood on a small knoll near the southwest corner of the ancient harbour, where the Palace of the Grand Master now stands. This castle was the headquarters of the Knights Hospitaller of St. John and was built in 1309 CE on the site of a 7th-century Byzantine chapel and fortress.[299] Italian excavations at the start of the 20th century revealed very substantial foundations

under the northwest part of the building that may have been the base of the Colossus statue. Unfortunately, the subsequent modifications to create a summer palace for the fascist leader Mussolini covered the remains, making it impossible to carry out further investigations. This location has a lot of promise: the site itself was almost the highest point of the city at 10 metres above sea level so that top of the statue would have been visible above the ship-sheds for a distance of about 25 km seawards. It was also close to an important street, which ran almost west-east behind the ancient ship-sheds, linking important buildings like the Temple of Aphrodite and a later Roman monumental gate, the Tetrapylon. Blocks found near the proposed site have inscriptions that show that a temple of Helios may have stood nearby.[290,301]. An on-land site would have made it easy to cast the sections of the statue nearby—indeed the best way to pinpoint the ancient location of the statue may be to find the foundries, most likely from fragments of the moulds. However, the foundry may have been a temporary affair, perhaps in a military ship-shed adjacent to the harbour where it would have been accessible for importation of raw metal and fuel, and close to the construction site. Finally, if the statue had been erected at either of these sites, then when it fell it would have been accessible for description by ancient writers. And fall it did, sixty years after it was finished.

Sometime between 229 and 225 BCE (usually ascribed to 226 BCE), an earthquake caused enormous damage to the city of Rhodes. The event was so significant that "international" aid poured into the island, partly to restore the trading capacity of the state on which so many of the neighbouring communities, especially Egypt, depended.[289]

The Colossus toppled, with only the calves remaining in place, according to Strabo, writing 250 years after the earthquake. This type of failure suggests that it may already have been weakened by corrosion, especially if it was erected near the sea (see box 7-1: Galvanic Corrosion). The aid package from Ptolemy III of Egypt included an offer of 3,000 talents of bronze (90 tons), with concomitant workmen and money for subsistence. We don't know if the Rhodians accepted

Box 7-1 Galvanic Corrosion

Corrosion is almost always a problem for metal structures exposed to the weather and the Colossus was no exception. It was particularly susceptible to *galvanic corrosion*, which occurs where two different metals or alloys are in contact and are soaked by salty water thus creating an electrolytic cell in which one of the metals will be dissolved.

For the Colossus, the most significant problem would have been the contact between the bronze skin of the statue and the iron framework, where wetted by sea spray, which would have converted parts of the iron clamps into soluble chlorides, allowing the skin to detach and weakening the statue. The same problem could also have occurred between batches of bronze or iron with slightly different compositions, or even impure bronze that had crystals of iron in it. In some situations, this problem could have been resolved by putting an insulating material, such as wood or leather, between the two different metals. We don't know if the statue builders did this, but insulation materials would not have lasted for the life of the statue and would have had to be replaced regularly.

this offer but Strabo mentions that they consulted an oracle, who advised them not to rebuild.

A popular story is that the remains lay untouched on the ground for almost nine hundred years until 654 CE when the Arabs invaded Rhodes. They broke up the remains and sold the metal to a Jewish trader on the mainland, who transported it to Syria on nine hundred camels. If this story was true, then it gives us another estimate of the weight of metal in the statue. A camel can transport about 150 kilogrammes, so the total weight would have been 135 tons. This agrees with the calculations for a cast statue with a skin 5 millimetres thick. However, this narrative seems rather unlikely—theft of unguarded valuable materials like bronze would have been inevitable—and one ancient source suggests a more plausible story.

In 311 CE, the Roman historian Eusebius compiled a chronology of important events that included mentions of the restoration of "A colossus"—unfortunately, it is not always clear if he refers to the Colossus of Rhodes or a huge statue of Nero in Rome, which was based on the Helios. The simplest interpretation of his work is that the Colossus of Rhodes was rebuilt after the 226 BCE earthquake, only to fall again in 107 BC.[303] Strabo's description may refer to this ruin. Restoration of the statue may have become somewhat of a tradition for Roman emperors: Vespasian (69–79 CE) and Hadrian (117–138 CE) both seem to have contributed to renovation costs but there are no details as to what was done. In 142 CE, a major earthquake occurred that may have destroyed Hadrian's restoration just after it was finished.[304] I wonder if the Rhodians felt that this was a repeat of their earlier experience and that perhaps the oracle had been right. If we have interpreted Eusebius correctly, then the life of the statue may have been 420 years and not the commonly proposed 60 years.

It may be possible to reconcile both these theories. If the Colossus was located to the southwest of the harbour, where the Palace now stands (Figure 7-4), then this site would have been disturbed in the early part of the 7th century CE when the Byzantines built a fort to protect Rhodes against Arab invasions. When they were digging the foundations, they may have come across fragments of the Colossus that had been deeply buried in rubble. If such material was put into storage, it could have been found by the Arab invaders and sold off. The story could have been exaggerated from the sale of some bronze fragments to the looting of the whole statue.

Geology and Landscape of Rhodes

We tend to look at the geology of islands differently than that of the surrounding seabed. However, in a continental region, the geology of islands is not so different from that under the sea—we just know much more about on-land geology. In the case of Rhodes, the island

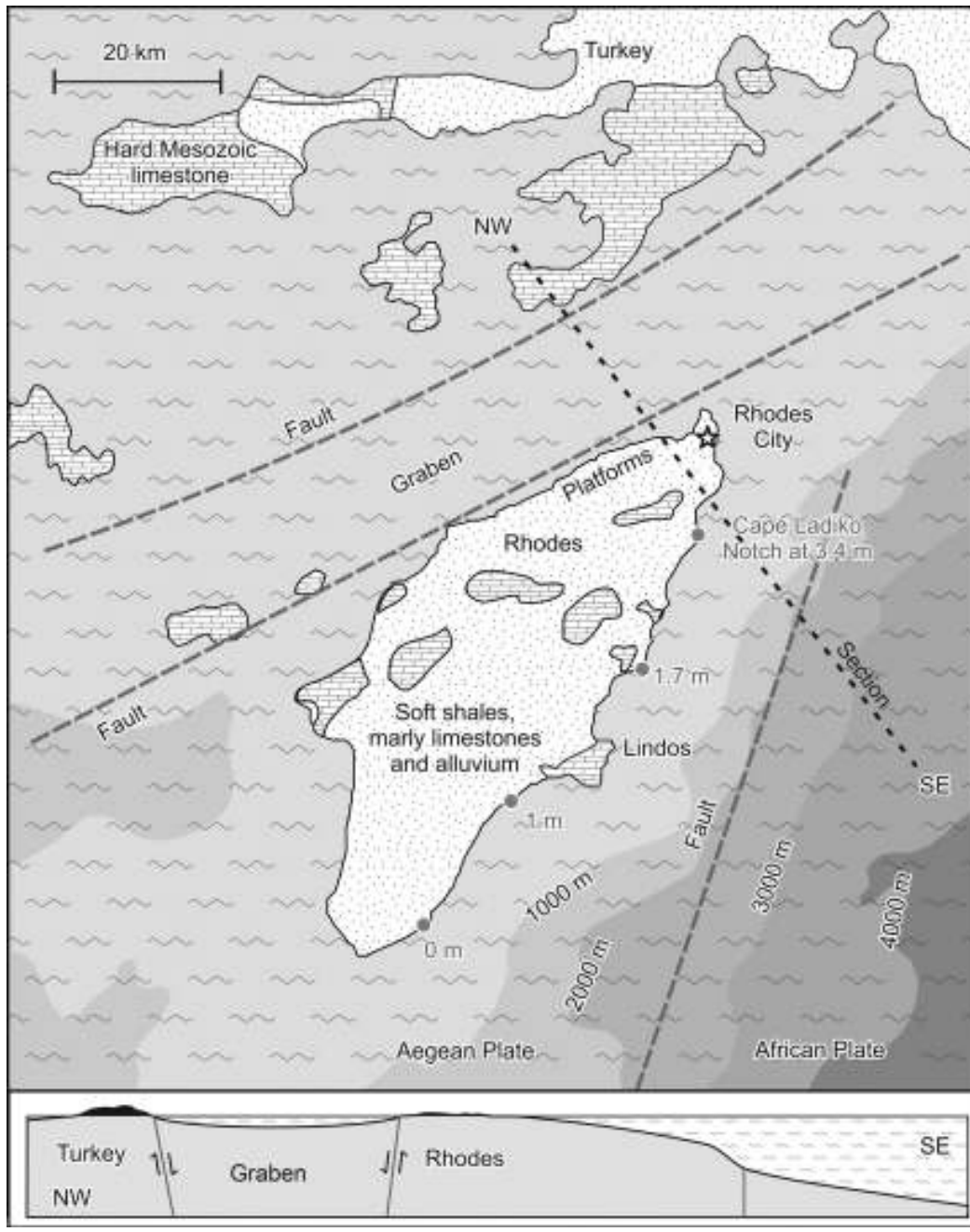


Figure 7-5: Hard limestones that resist erosion underlie the highlands of Rhodes. Most of the other rocks on the island are soft shales and marly limestones that weather to make good soils. Major faults have moved regularly in the past: such movements created the graben that underlies the strait between Rhodes and Turkey, and also tilted the northern part of the island. Map by author after Howell, A., et al., 2015, "Late Holocene uplift of Rhodes, Greece: Evidence for a Large Tsunamigenic Earthquake and the Implications for the Tectonics of the Eastern Hellenic Trench System." *Geophysical Journal International* 203(1): 459–474; Kontogianni, V.A., N. Tsoulos, and S.C. Stiros, 2002, "Coastal Uplift, Earthquakes and Active Faulting of Rhodes Island (Aegean Arc): Modeling Based on Geodetic Inversion." *Marine Geology* 186(3–4): 299–317.

has only been cut off from the Turkish coast for a few million years. It did not break away from the mainland but was isolated by the formation of a valley, now under up to 400 metres of water (Figure 7-5). This valley is a graben—a part of the earth that dropped down between two faults—produced in response to north-south stretching of the crust in western Turkey and the adjacent part of the Aegean Sea (see box 6-3: The Aegean Coast of Turkey).

To the south of the island, the seafloor drops off abruptly to over 4,000 metres deep. In this area, the Aegean and African tectonic plates meet in a complex, active boundary, along a series of NE-SW faults (Figure 1-2 in Chapter 1). The relative movements of the two plates produce frequent earthquakes, which had devastating consequences for the island—and the Colossus. These earthquakes also produced many features of the local topography.

The landscape of the island is influenced by both the nature of the underlying rocks and recent uplift and subsidence.[298] A hard, grey limestone makes up much of the highlands of Rhodes, and also the islands and mainland to the north (Figure 7-5). The same limestone is also seen on other Aegean Islands and continental Greece. In antiquity, better quality buildings were commonly made of this stone. It was also important for water supply because some of the rain that falls on the hills disappears underground to reappear at perennial springs, such as Epta Piges near Rhodes ("Seven Springs"; Figure 4-7).

This limestone originated 150 to 250 million years ago when the region had a tropical climate and was joined to Africa. Shellfish, other invertebrates, and bacteria flourished in a warm shallow tropical sea, rather like that around the Bahamas today. This continued for such a long time that a thick pile of sedimentary beds accumulated here. Later, the crust underlying this shallow sea split from Africa during the creation of a new ocean basin within the continent, rather like the way that the Red Sea has split Arabia from Africa. Expansion of this oceanic basin created an ancestor of the Mediterranean Sea and forced the land northwards, where it collided with Eurasia, making a chain of mountains now in Greece and Turkey.

As soon as several hundred metres of loose sediments had accumulated, those at the base become transformed into rock by a process called lithification. First, the weight of sediments increased the pressure, forcing out water so that the pores between the particles closed up. Second, the crystallization of new mineral grains between the particles glued them together. This cement is actually derived from the sediments themselves: the process started when percolating waters dissolved the smaller fragments; later on carbon dioxide gas was dissipated from the solution and calcite ($CaCO_3$) crystallized between the fragments bonding them together.

Much of the lowlands of Rhodes are underlain by a soft, clay-rich limestone called marl, a rock which has shaped parts of the history of the island. The marl formed about five million years ago when most of the island was submerged, except for small, low islands. Erosion of the land shed clay into the shallow water where it mixed with calcite mud and shells. Such marls weather easily to produce good soils, which are scarce in this part of the Aegean. The clay in the soil retains moisture from the winter rains and made for productive agriculture: this, in turn, supported a significant population on the island and enabled the development of the society that produced the Colossus.

The development of the city of Rhodes was influenced by another important rock: coquina limestone, locally called *poros* (Figure 7-6). This limestone is made of broken shells, a few millimetres long, loosely cemented together. The shellfish lived one to two million years ago in a vast expanse of shallow water that stretched 50 km to the south. Storms broke apart the shells and piled them up. Some of these piles were cemented into a rock where they accumulated in the shallow seas and on beaches, but others were blown by the wind into dunes, and then cemented afterwards. The rocks were never strongly cemented as they had never been subjected to high pressures and temperatures, unlike the hard, grey limestones of the highlands.

Coquina limestone has several special qualities. It is very porous and hence water would rapidly percolate through to the underlying rocks, where it accumulated and could be extracted from shallow

Figure 7-6: The Greeks built a temple dedicated to Apollo, or possibly Helios, on the ancient acropolis west of the city, now called Ayios Stephanos. The foundations stood on a thin bed of coquina limestone overlying soft marl. Coquina is made of weakly cemented shell fragments from ancient beaches or dunes. It is only a few metres thick and was used extensively for construction. Photo courtesy of the author.

wells, providing an essential resource during the long dry summers. Coquina is soft and easily cut using simple tools and was much used for rough construction, although for their temples the Greeks preferred more durable materials, such as the older limestones exposed in the hills. The Romans, and later the Crusader Knights of St. John, were not so fussy—they wanted to build fast and were less concerned with posterity—they used coquina to make the castle, the city walls, and many other buildings. There was an additional quality that the Crusaders favoured—coquina masonry was particularly resistant to impact from cannonballs, as the rock just compacted instead of cracking. The quarries were in the city and to the southwest.[307] Some of these quarries were excavated down to sea level so that the rock could be easily loaded onto ships, inadvertently providing reference points for sea level at that particular time (Figure 7-13).

Pindar's geomyth that the island had risen recently from the sea may have been inspired by the presence of ancient seashells in the coquina and marly limestones found far above sea level and also by observations of uplift after earthquakes shook the land.

Although Rhodes was well furnished with building materials and had agricultural wealth, the island had no metal deposits with which to construct the Colossus. Metals had to come from distant sources, down long-established trade routes.[208]

Copper and Other Metals

The development of metallurgy was so important in human history that we have named major cultural periods after metals: The Copper (Chalcolithic), Bronze, and Iron Ages. Copper was first used extensively in Europe and the Middle East in 5000 BCE.[308] However, the Colossus was made of bronze, an alloy of copper and tin. The ancient discovery that the addition of tin to copper made a much harder and more useful metal was a major technical advance, which marked the transition to the Bronze Age in about 1700 BCE. Bronze has additional

advantages: pure copper solidifies at 1084°C, whereas bronze solidifies over a temperature range from 1020 to 850°C, so it is easier to melt and cast. When the Colossus was made, bronze was usually made with about 8% tin, together with some lead to further reduce the melting temperature and make it easier to cast. Alloys such as bronze melt at a lower temperature than pure metals because the presence of different types of metallic atoms leads to a less regular arrangement of atomic bonds, which are hence weaker and so more easily broken by increasing thermal vibrations as the temperature is raised.

Construction of the Colossus may have used bronze and especially iron recycled from Demetrius's abandoned siege engine, but much new metal must have been obtained especially for the project. We know that long-distance trade in metals was well established because shipwrecks carrying copper and tin ingots have been found (see box 7-2: An Ancient Metal-Transporting Ship). The question now is how were the deposits formed and which ones were exploited at the time of the Colossus?

Copper is not a particularly rare metal and occurs in many deposits both small and large throughout the Mediterranean region. The most common copper ore is the mineral chalcopyrite ($CuFeS_2$), a yellow shiny sulphide mineral. However, this mineral is unstable at the surface

Box 7-2 An Ancient Metal-Transporting Ship

A 15-metre-long ship was transporting metals and other valuable goods along the Aegean coast when it sank near Uluburun, Turkey in about 1300 BCE. It had hundreds of *oxhide* and disc-shaped copper ingots in its hold, equivalent to 10 tons of metal, as well as a ton of round tin ingots, in the right proportions for making bronze. There was also a lot of Cypriot pottery on board, suggesting that the boat, and presumably the metal, had come from Cyprus. The coastal trade from Cyprus to the Aegean was still active using similar ships when the Colossus was constructed almost a thousand years later.[328–330]

where it reacts with air and water to make a range of new minerals, including metallic copper, bright green malachite ($Cu_2CO_3[OH]_2$), and blue azurite ($Cu_3[CO_3]_2[OH]_2$), as well as darker iron oxides (Plate 14a). Natural metallic copper was the first source of the metal but is rare in the Mediterranean region, unlike in North America, and was soon exhausted. After that people turned to the coloured minerals and finally to chalcopyrite. I'll discuss later how they smelted these ores, but first I want to talk about the "Copper Island" of Cyprus.

Cyprus was the major source of copper in the Mediterranean region from the second millennium BCE to the 8th century CE.[309] Indeed, the word *copper* comes from the Latin word *cuprum*, in turn derived from *aes Cyprium*—"Metal of Cyprus." At the time of the Colossus, Cyprus was an economically important part of the empire of Ptolemy I of Egypt, valued for its resources of copper and wood. Remember that it was Ptolemy I that ordered the construction of the Pharos and rescued the Rhodians from the siege of Demetrius.

Almost all copper produced on Cyprus was exported, but we can tell how much was made by looking at the waste products of refining, which were valueless and so left in place. The amount is remarkable—over 200,000 tons was produced on the island, mostly in the two thousand years before the Romans (Figure 7-7). At a mean production rate of 100 tons a year, the copper in statue could have been produced in a year or two. Hence, Philo was somewhat exaggerating the demands of the statue on total copper production.

The copper deposits of the Troodos Mountains were originally formed deep on the ocean floor (Figure 7-7, Figure 7-8).[311,312] The deep oceans far from land are geologically very different from the continents: the outermost layer, the oceanic crust, "floats" on denser mantle rocks. This crust is generally formed at underwater ridges, such as in the middle of the Atlantic Ocean but can also form behind volcanic island arcs, as was the case for Cyprus. Everywhere in the earth, temperatures increase with depth: heat generated deep down must diffuse outwards towards the surface. At depths of 100–50 kilometres, temperatures were sufficient to melt the earth's mantle and produce

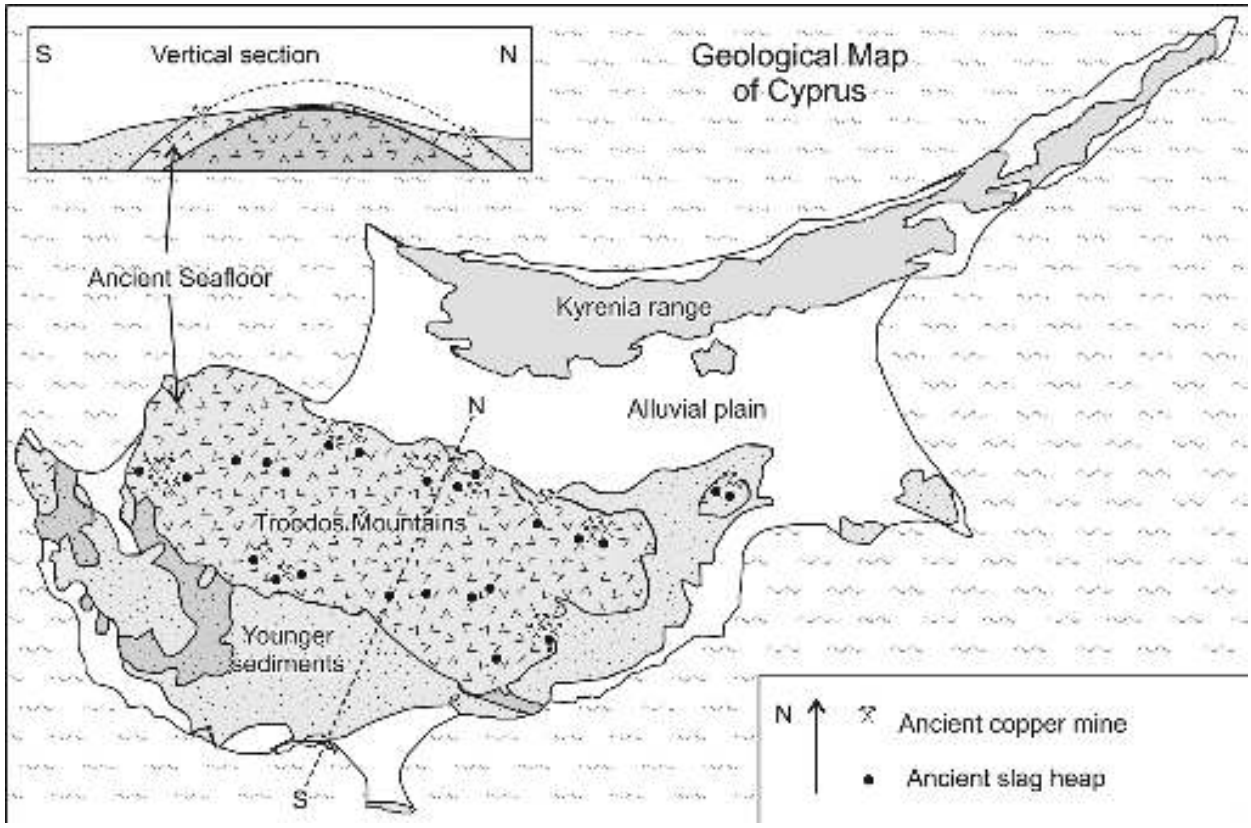


Figure 7-7: The most important sources of copper in the western part of the ancient world were in the Troodos Mountains of Cyprus. The mines occur in a section of ancient seafloor, which had been preserved in the centre of a huge fold (see the section in the inset) that pushed the rocks from the deepest part of the oceanic crust to the highest parts of the mountains. Most of the mines were located around the edge of the mountains, in the "pillow" lavas that had erupted underwater. Map by author after Cyprus Geological Survey.

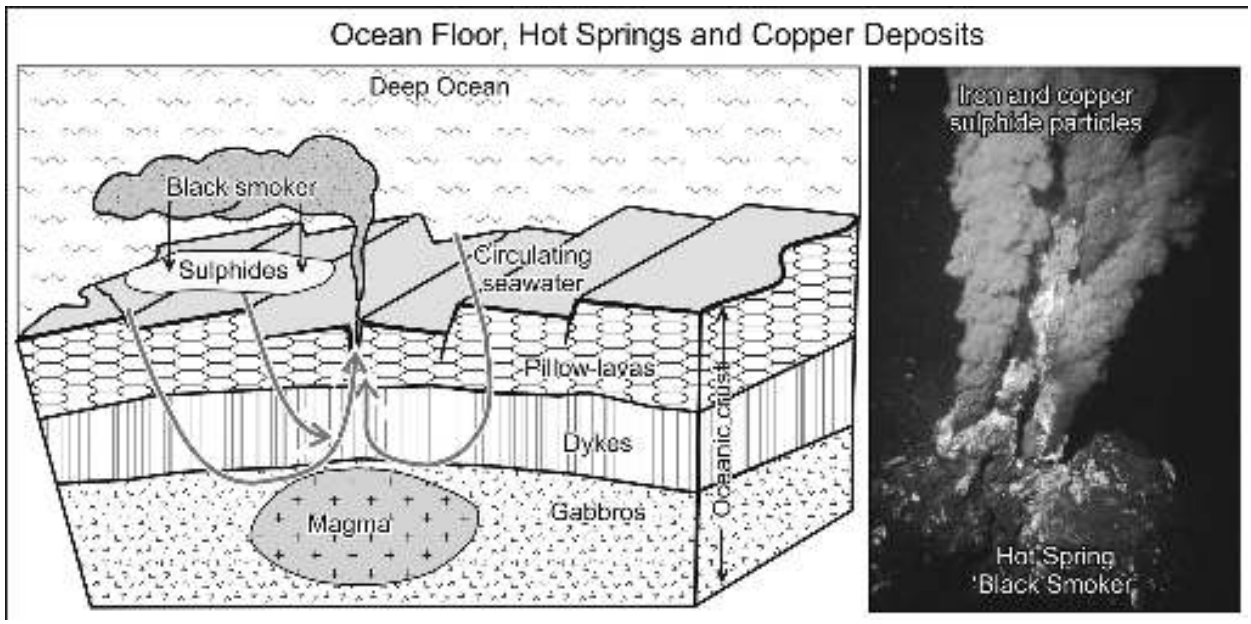


Figure 7-8: The copper ores of Cyprus were formed by the precipitation of sulphide minerals from very hot springs issuing from the seafloor. Image by author after NOAA photo library; Butterfield, D.A., 2000, "Deep Ocean Hydrothermal Vents," In Encyclopedia of Volcanoes, H. Sigurdsson, Editor, Academic Press, San Diego, 857–875.

basaltic magma, which rose to within a few kilometres of the seabed. Here, some of the magma either solidified in cracks to make sheets of rock called dykes or continued to the seafloor where it erupted as lava flows. These underwater lava flows are called pillow lavas, as the rocks resemble piles of pillows 1 to 2 metres long (Figure 7-8). Seawater circulating through the pile of hot rocks reacts with some of the minerals, including those containing copper. This heated water issues as underwater springs, which are rapidly cooled by seawater, precipitating minerals including iron and copper sulphides to make a plume of "black smoke." Subsequent accumulation of these minerals on the seafloor makes deposits of copper and other metals.

The copper deposits in the Troodos rocks were created in this way ninety million years ago in the ancient Tethys Ocean, which lay between Africa and Eurasia. Large-scale global tectonic movements forced the two continents together and an arc of the oceanic crust was forced to descend hundreds of kilometres into the earth at an angle of about 45 degrees. The Troodos seafloor was formed by local stretching of the oceanic crust behind the arc. This is what is now happening between Japan and the Asian coast. Continuing overall convergence thrust this part of the oceanic crust over adjacent parts of the oceanic crust. Finally, two million years ago, the landscape of the island we see today was formed, when part of the island was uplifted by a further 2,000 metres creating the Troodos Mountains, where the copper deposits were found.[313]

Exposure to rain and air during the last two million years altered the copper-bearing rocks. Chalcopyrite in the volcanic rocks broke down, delivering copper to the groundwater, which transported the metal tens of metres downwards. Here, new copper minerals formed, making a richer deposit than was found in the original rock—this was the zone favoured by the miners in antiquity. The process left dark rocks at the surface, whose presence was used by the ancient miners to locate underlying copper deposits.

Most ancient mines were developed underground, using vertical shafts and horizontal galleries or adits cut in from the valley sides

Figure 7-9: This votive plaque from about 570 BCE shows miners and children working underground, illuminated by a lamp suspended from the roof. The archaeological context of this object suggests that they were extracting clay, but a metal mine is likely to have been very similar. Image by author after photo © Marcus Cyron / Wikimedia Commons, CC BY-SA 3.0

(Figure 7-9).[314] In Cyprus, the deepest excavations went to a depth of 180 metres, but most were much closer to the surface.[315] The depth was limited by ventilation and water infiltration, as there were no mechanical methods for mine drainage until slave-powered waterwheels were developed by the Romans for their mines at Rio Tinto, Spain. The ore-bearing rock could be cut relatively easily using bronze or iron pickaxes and chisels as it was not uniformly solid: the host rock was pillow-lava flows and the sulphide ore minerals were commonly partly altered by rainwater infiltrating from the surface. However, that is not to say that conditions were pleasant: Slaves or prisoners of war were commonly used, as well as free men (see box 7-3: Conditions in the Cyprus Mines).

Box 7-3 Conditions in the Cyprus Copper Mines

The only eyewitness report from the Cyprus mines was by the physician Galen (Claudius Galenus) in 166 CE.[331] He was researching copper sulphate, which was used as a medication. He wrote:[332] "But to me, all the times I descended to the end of the tunnel where the warm and green yellowish water was collected, the air which smelled of khalkitis [sulphur?] and copper rust seemed to me to be stifling and oppressive. The taste of the water was the same. The naked slaves brought up the amphorae running and they could not stand to stay therefore a long time, but quickly ascended. Neither the lamps which were lighted on both walls of the tunnel in symmetrical spaces could stay lighted for a long time, but instead were extinguished."

Native copper may have never been present on the island of Cyprus, so the earliest ore to be exploited must have been the carbonate alteration minerals (Plate 14a). The first smelting of copper was likely accidental, as, for example, when a potter tried to use coloured copper minerals to make a glaze and there was not enough oxygen in the kiln. Under these conditions, some of the copper minerals may have been reduced to metal. Later on, smelting would have done in specialized ceramic pots or kilns by combining the ore with charcoal and heating the mixture over a fire.[229] However, the temperature would not have been high enough to make liquid metal—pure copper melts at 1084°C—so instead a metallic sponge would have been produced, which could have been heated and hammered to make copper tools and weapons. Later on, bellows were used to blow air into a furnace, heating the charge above the melting temperature of copper. The liquid metal would then accumulate below a crust of waste products.

The most common copper ore mineral in unaltered rocks, chalcopyrite, cannot be smelted directly with charcoal so new techniques had to be developed once the surficial deposits were exhausted.

Unfortunately, we don't know exactly how this ore was smelted[316,317]—the challenge is to separate the copper from the iron in this mixed sulphide ($CuFeS_2$). If iron remains in copper, then it forms tree-like crystals that make the metal susceptible to galvanic corrosion (see box 7-1: Galvanic Corrosion).

All chalcopyrite smelting methods start with "roasting" the ore to convert part of the sulphides to oxides. This process gives off lots of heat, so it is just necessary to light the pile of crushed ore and it will burn for days, releasing clouds of the toxic gas sulphur dioxide. In the best-known process, the roasted material was mixed with charcoal and a flux, commonly quartz sand, and heated in a furnace until it melted and separated into two liquids. The upper, lighter liquid was slag and contained some of the iron; the lower liquid, now called "matte," has all the copper in the form of sulphide and some of the iron. The slag may have been tapped and poured off, or allowed to solidify in place. The matte was then separated, mixed with charcoal and sand, and melted in the upper part of a furnace. As the matte melted and dripped down, iron was oxidized and went into a new layer of slag. It may have been necessary to repeat this process until all the iron had gone, at which point copper sulphides and oxides in the matte reacted to make copper metal and sulphur dioxide. The first part of the smelting may have been done at the mine site to produce the matte, which was then moved to refineries on the coast for final processing.

No complete smelting furnaces survive, but we have lots of fragments. It appears that the furnaces were not that different from those used to melt metal for casting (Figure 7-3).[317] The raw materials, ore, flux, and fuel, were added to the furnace and ignited from an opening at the base. Once the fuel was burning, air was blown into the base of the furnace using bellows to increase the temperature.

It is clear that copper was available in large quantities, but what about tin, the other major ingredient of bronze? Tin is a much rarer element than copper and usually occurs in very different geological settings. It does not occur as a native metal, but commonly as the oxide cassiterite (SnO_2), a black mineral that is associated with some

granites. As minerals crystallized from granite magma, tin was concentrated in the remaining liquid, which finally escaped along cracks into the surrounding cooler rocks where cassiterite and other minerals crystallized out. There are other, less important types of tin deposits but it is not clear how much they were exploited in antiquity.

As with copper, it may have been potters who first discovered metallic tin. Alteration of granite by circulating hot water converts much of the rock into a white clay called kaolin ("china clay"), which is the raw material of porcelain and other types of pottery. If cassiterite was present in the original granite, then it would have been conserved in the clay. Since cassiterite can be smelted to tin by heating to just 600°C, the firing of clay containing the ore would have produced specks of metallic tin in the pottery. However, the quantity of cassiterite in such clays is very low and further geological processing is needed to make an ore deposit suitable for exploitation. Cassiterite is a heavy mineral, and like gold can be found concentrated in placer deposits along streams (Figure 4-9). Indeed, tin may initially have been a byproduct of placer gold mining.[318]

The eastern Mediterranean region has no significant tin deposits meaning that long-distance trade must have been established early in the Bronze Age. Some metal may have been obtained from central Asia, perhaps along the same trade route as the gem material lapis lazuli (see box 2-3: Gemstones and Imitations), but most appears to have been obtained from Bohemia, Iberia, Brittany, and especially southwest England, probably by Phoenician traders and their intermediarie.[319,320] The wet, mild climate of Europe accelerated weathering and erosion of ore, producing easily exploited placer deposits, but when these were exhausted interest turned to direct mining of the ore. European tin sources fit with the observations of Herodotus, who mentioned that the metal came from the Cassiterides, islands somewhere in northern or western Europe.

The last ingredient of much bronze was lead. Like many other metal deposits, warm or hot metal-enriched watery fluids were generated at depth, ascended along faults, and finally reacted with marble

and limestone to produce crystals of lead and zinc sulphides. Lead was mined at many places in the Aegean region, but particularly just south of Athens at Lavrion.[170] Here, what the miners really wanted was silver, which occurs as an impurity in the mineral galena (see box 6-2: Money and Minting). Lead was thus a byproduct, readily available and inexpensive. There were hundreds of small mines near Lavrion, mostly worked by slaves in deplorable conditions, whose silver financed many of the great buildings of classical Athens, such as the Parthenon.

The skin of the Colossus may have been bronze, but Philo tells us that it had a core of stone and iron. The iron was used in several ways: to tie stone blocks together so that the structure could resist earthquakes and to provide or strengthen a framework to support the bronze skin.[321] Raw forged iron (not steel) is weaker than bronze, so why did they use it? It may have been because they had used up all readily available tin, or that iron was cheaper than bronze, or that they had a lot available from the siege tower.

Although iron is an abundant element, it is difficult to extract. At the time of the construction of the Colossus, iron was produced by packing iron ore, charcoal, and a flux together in small ceramic shaft furnaces, which were heated to 1000°C over charcoal using bellows (Figure 7-3).[322] Solid iron grains formed in a silicate liquid (slag). The final product was a spongy mass of solid metallic iron, which was heated and hammered to drive out most of the slag. The presence of residual slag had a beneficial effect: it made it possible to weld together iron pieces just by hammering.

We cannot tell where the iron for the Colossus came from, but one of the most important sources in the region was the island of Seriphos, one of the Cycladic islands in the central Aegean Sea.[170] The amount of ancient slag shows that about 7 million tons was produced here. The Seriphos ores are associated with a granite intrusion: watery solutions released during the crystallization of this rock reacted with the limestone to produce deposits of iron. This process is similar to that which produced the tin deposits, but for chemical and thermal reasons the two elements do not occur together.

Supplies of copper, tin, lead, and iron to build the Colossus were readily available in the eastern Mediterranean—the quantities involved were significant, but not that large. Hence, the limiting factors were more artistic, technical, and political. In the end, despite the immense effort and resources used to build the statue, it was felled by an earthquake in 226 BCE, only sixty years after it was finished.

This earthquake was so large that the city walls, the arsenals, and many residential buildings were brought down with much loss of life, as was the case on neighbouring islands and along the mainland.[185] The effect on the city of Rhodes was so significant that for several years afterwards coins featured a woman wearing a mourning veil instead of the usual images of Helios and a rose.[323] Earthquakes are common in this region. Let's now examine why they happen and how we can identify ancient events.

Earthquakes

The ancient Greeks believed that Poseidon caused earthquakes when he struck the earth with his trident—the importance accorded to this god is commensurate with the high frequency and severity of earthquakes in the Aegean region (Figure 7-10).[324] Many of the major earthquakes here are produced by movements along faults associated with tectonic plates or other large-scale crustal structures (Plate 1b).

We talk often about earthquakes, but what do we mean by that word? Actually, two different things: the cause, which is the sudden movement of two blocks of rock along a fault (crack) in the earth's crust; and the effect, which is the intensity of local vibrations that we perceive and which knocks down buildings and statues. This is why there are two different numerical scales for describing earthquakes and their effects. The well-known Richter scale, on one hand, expresses the total energy released by the earthquake. The biggest earthquakes are over magnitude 9. The Mercalli scale, on the other hand, quantifies the local intensity of the shaking and runs from I (low) to

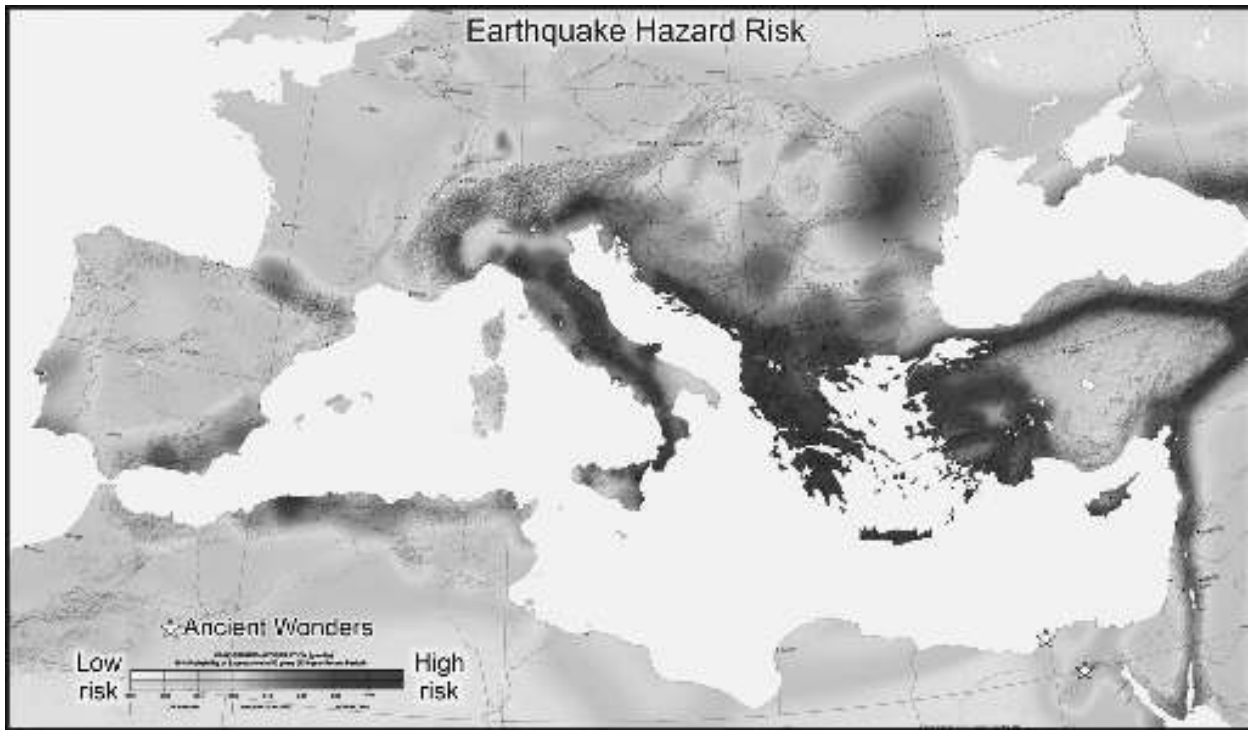


Figure 7-10: Earthquake hazard risk is the greatest level of shaking that can be expected with a certain probability during a given period, typically fifty years. The Aegean region has some of the highest levels of seismic risk in the world. Image by author after Giardini, D., M.-J. Jimenez, and G. Grunthal, 2003, European-Mediterranean Seismic Hazard Map, European Seismological Commission.

XII (high). Close to the earthquake's centre, shaking is more intense, with greater damage to buildings. Hence, for each earthquake there is only one Richter magnitude (energy) but different Mercalli intensities (shaking) at different places.

When a fault moves, it sends off four different kinds of seismic waves (Figure 7-11). P ("pressure") and S ("shear") waves go down deep into the body of the earth and can travel across the globe. P waves are faster than S waves and arrive first. Their arrival times are used to locate distant earthquakes, but they produce few problems as the movements associated with them are generally small. It is the waves that travel along the surface of the earth that do the most damage: the charmingly named Love waves shake the land horizontally and the Rayleigh waves shake it vertically, arriving some time after the waves that go deep in the earth. Surface waves can be amplified by resonance

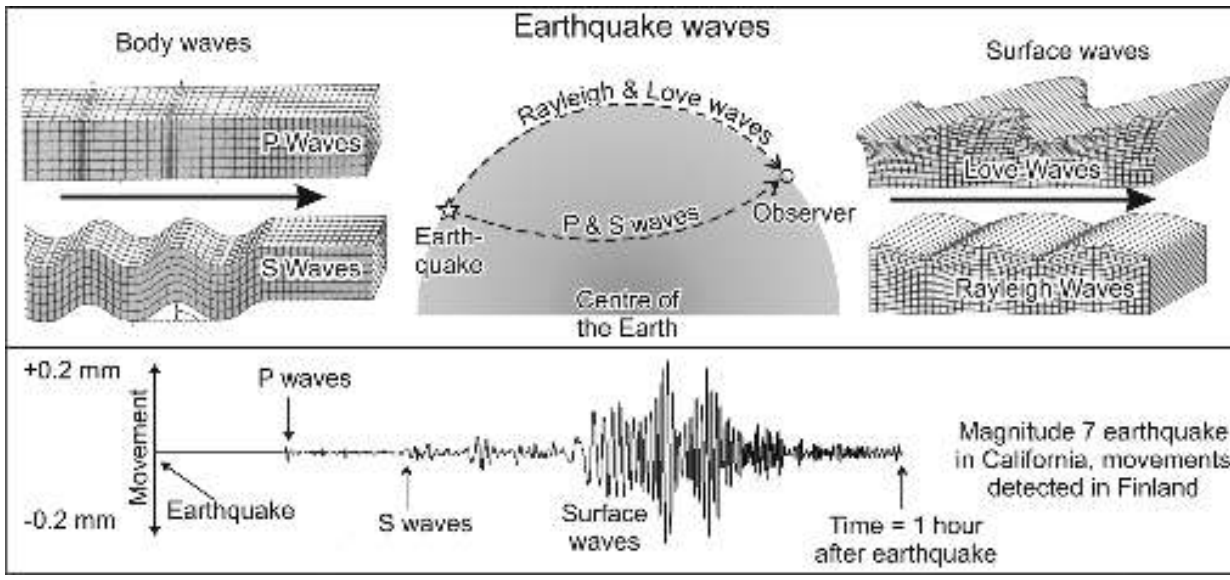


Figure 7-11: Earthquakes produce four types of seismic waves: P waves that travel deep through the earth and arrive first, followed by S waves. Rayleigh and Love waves travel more slowly along the surface and produce larger vibrations, which are more destructive. Image by the author.

("ringing") of loose sediments close to the observer. Surface waves contribute most of the shaking measured by the Mercalli intensity scale and it was these waves that toppled the Colossus.

The difference in speed of the different seismic waves is considerable—2 to 4 seconds per 10 km distance for close earthquakes—so that the smaller vibrations of the P waves can warn us about the imminent arrival of the more destructive surface waves. This may be why so many people can recall nighttime earthquakes and possibly why animals have been seen to come out of their burrows before the arrival of the surface waves.

Today we can determine the position and movements of faults from geophysical observations of earthquakes: seismographs at many different locations record the vibrations, to which we can add precise GPS positions of the land around the fault and other geological observations. We do not have this depth of knowledge for earthquakes that occurred more than one hundred years ago: inland, we can only study walls and columns that have collapsed, and sometimes the cliffs and cracks formed where a fault reached the surface (see Chapter 6

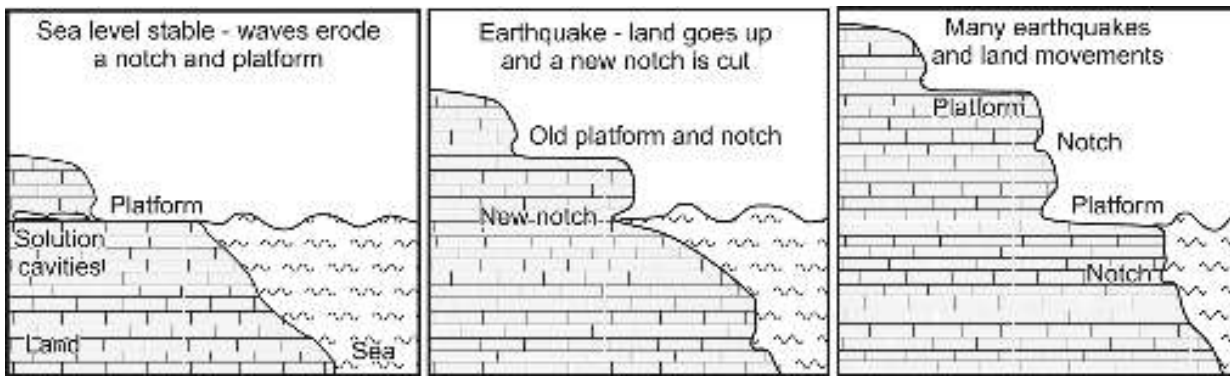


Figure 7-12: When sea level is stable, coastal erosion of a cliff will make a notch that may develop into a platform. If the land rises or sinks during an earthquake then the old notch will be preserved, leaving a record of the ancient position of sea level, and a new notch will be formed. Image by the author.

for a special situation). However, the context is different along the coast, where ancient sea levels can give us much information.

Movements of rock during an earthquake can change the height of the land with respect to sea level by up to 10 metres: the amount depends on the size of the earthquake, its distance from the coast, its depth and the orientation of the fault. The Mediterranean is an ideal place to observe ancient sea levels because the tide is generally less than 10 centimetres: erosion by the sea waves is thus concentrated at only one level and as a result cuts sharp notches in the cliff faces, which can develop into platforms and later into beaches (Figure 7-12, Figure 7-14). These notches develop particularly rapidly in softer rocks, especially limestone, for which there is an additional effect: the rock is weakened by the development of solution cavities along the water table, which is close to sea level near the coast (Figure 4-7). There are many such notches around Rhodes and the younger ones may be dated using shells that grew on the rock surface near the notch or that were cast up on former beaches.

Notches give the relative local position of the land with respect to the sea, but has global sea level changed recently? I have mentioned the low level of the sea during the last coldest period of the glacial period twenty thousand years ago when much of the earth's water was stored on-land in glaciers (see box 6-6: Sea Level and Cultural

Developments). Since that time, the melting of ice has refilled the sea, drowning old notches below current sea level. Melting was essentially complete by seven thousand years ago, so local changes in sea level since then are due to movements on faults. A minor complication is a rise in global sea level of about 20 centimetres during the last 140 years produced by anthropogenic climatic warming.

Because of the proximity of the Aegean tectonic plate edge to the south, and extensional rift valleys to the north, there have been large and rapid changes in the height of the land with respect to sea level here (Figure 7-5). Over the last few hundred thousand years, tectonic forces have tilted Rhodes to the southeast—we can deduce this from a series of platforms and former beaches situated up to 100 metres above sea level along the northwest coast of the island. We can also see this tilting around the city of Rhodes: the bed of coquina limestone that covers much of the city was originally deposited close to sea level, but now it ramps up from near sea level in the east to 110 metres above the sea at Ayios Stephanos, the ancient acropolis. This ramp is cut off to the north by an east-west fault that follows the southern limit of the ancient harbour (Figure 7-5). We can infer changes in land height during the last seven thousand years from up to eight different wave-cut notches in sea-cliffs and former beaches perched above the sea, as well as from the height of coastal quarries, quays, and fish-storage tanks[305–307] (Figure 7-12, Figure 7-13).

Along the southeastern coast of Rhodes, there is a prominent notch that increases in height northeastward, reaching 3.4 metres above sea level about 7 kilometres south of Rhodes City, where it terminates. Dating of dead barnacles and shells still clinging to the rock in the notch give an age of 300 BCE (Figure 5, Figure 7-14). There are also many Roman quarries along the coast that are now submerged to a depth of 40 centimetres. Even if we allow for sea-level rises of up to 20 centimetres produced by climate changes during the last century, then it is still evident that the land has gone down since that time, probably during the 1481 CE earthquake[325,326] (Figure 7-13). If we add these effects, we can deduce that the land must have risen by a maximum of

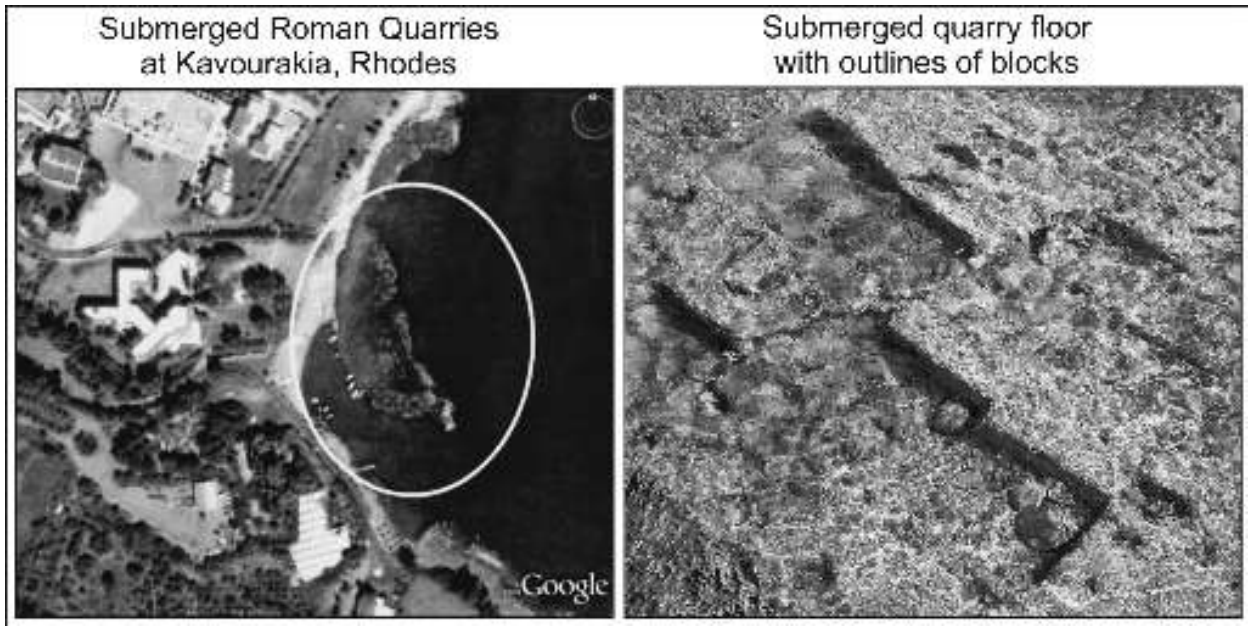


Figure 7-13: The Romans quarried coquina stone at Kavourakia, six kilometres south of the ancient harbour of Rhodes. They excavated down to sea level so that the 80-centimetres-long blocks could be easily loaded onto boats. The sea now covers the quarry floor to a depth of 40 centimetres, showing that the relative sea level has changed since excavation. Image by author after author's photo and Google Earth image.

3.8 metres between 300 BCE and Roman times. It used to be thought that this uplift occurred during a single huge earthquake in 226 BCE, which toppled the Colossus for the first time, but it is now clear that the story is more complicated.[305,306]

The harbour was lined with ship-sheds whose base is a good indicator of sea level at the time of construction. Excavators have found that the bases of ship-sheds constructed before 226 BCE were repaired by the addition of 1 metre of stone—so there must have been subsidence during the 226 BCE earthquake, making the water deeper, and not uplift[327] (Figure 7-14). This is still a very substantial movement and the earthquake would have been powerful enough to have toppled the Colossus. There is a fault that crosses the island just south of the harbour and movements there could have produced the earthquake (Figure 7-4). Indeed, one of the favoured sites for the Colossus was on the scarp just above this fault, which would have made it particularly susceptible to such an earthquake. The ship-sheds are now over 3

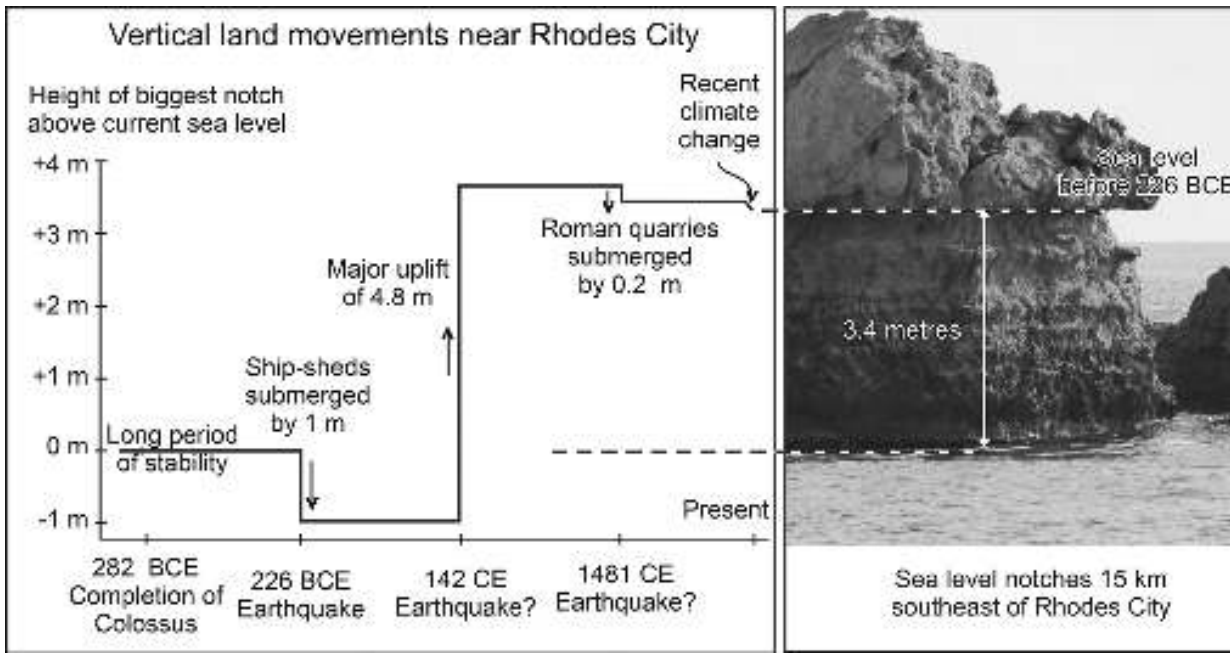


Figure 7-14: A prominent notch at Cape Ladiko, southeast of Rhodes City, formed at sea level during a long period of stability that ended with the 226 BCE earthquake. This notch is a good monitor of changes in the height of the land with respect to sea level since the construction of the Colossus and is now at 3.4 metres. Recently, human-induced climate warming has resulted in an overall sea level rise of about 20 centimetres. Image and photo courtesy of the author.

metres above sea level, so they must have been uplifted during another powerful earthquake sometime after 226 BCE and before the excavation of the Roman quarries (Figure 7-14).

An earthquake that could move the land upwards by 4.8 metres at Rhodes, and lesser amounts along the whole southeastern coast, must have been either a single huge event, or a series of large earthquakes (Figure 7-5, Figure 7-14). Some ancient writers mention a series of major natural disasters occurring around 199 BCE, but they may have been referring to a tsunami produced by an eruption of Thera volcano. The most likely culprit was an earthquake in about 142 CE, which we know caused significant damage as another international relief fund was set up to help cities along the coast east of Rhodes.[306] Since there are no other prominent notches close to sea level, this earthquake must have been the largest earth movement in the region since global sea level stabilized seven thousand years ago (see box 6-6:

Sea Level and Cultural Developments). The earthquake was probably located along a major fault to the southeast of Rhodes (Figure 7-5). Uplift of the land was greatest in the northern part of the island as it was closest to the epicentre of the earthquake. After this event, the harbour floor was raised over 4 metres and must have been left mostly dry.[327] Such a large earthquake may have been accompanied by a large tsunami, which would have contributed to the destruction on Rhodes and in many parts of the eastern Mediterranean.[305] We don't know what happened after this uplift but it was technically possible to have dredged the harbour and restored its function, if very expensive (see box 6-7: Dredging Techniques).

The seismic history of this region has continued since the end of the Colossus, with major events in the eastern Mediterranean in 365 CE, 1303, and 1481 (see Chapters 5 and 8). The last of these earthquakes may have caused subsidence that we see today in submerged coastal quarries (Figure 7-13), but the overall destructive effects on Rhodes were probably minor.[306] In the future, there will be other major earthquakes here, but despite our vastly increased knowledge, we cannot yet predict exactly when or where they will occur or the damage that they will produce.

Epilogue

The Colossus was the greatest statue of its time, even though larger statues were constructed later. Indeed, the name was subsequently used to describe any large statue, and finally to describe any large object or even a prominent person—as I mentioned before, Emperor Nero erected a huge statue of himself based on the Colossus of Rhodes, from which the neighbouring Flavian Amphitheatre takes its common name, the Coliseum. If the Rhodian Colossus was restored by successive Roman emperors, as Eusebius suggested, this would have maintained its fame and prestige for over four hundred years. Now all that remains is the name.

If the Rhodians had indeed constructed the Colossus where the Palace of the Grand Master now stands, then perhaps archaeological investigations of the surrounding area may be worth carrying out. It may be possible to get some idea of what lies under the palace by using geophysical methods, but it will not be easy. Indeed, we may have to wait for another substantial earthquake to bring down the existing structures so that we can start new excavations that may reveal the base, or even fragments of the statue itself, perhaps resolving centuries of speculation about this wondrous structure.

8

The Pharos at Alexandria

Alexandria and the Pharos

The Pharos was the only one of the ancient Wonders that had any practical use: guiding boats along this low, featureless coast to the harbour of Alexandria, which was the greatest trading city of the ancient Mediterranean world (Figure 8-1). It was the last of the Wonders to be built, the last to be included in the canonical list, and possibly the most widely known, its fame spreading as far as Persia and China. It was also the only one financed and constructed by a private citizen. But even so, it became the symbol of the royal city of Alexandria, founded by Alexander III of Macedon, later known as Alexander the Great.

In 334 BCE, Alexander left Macedonia to finish a project started by his father, Philip II: breaking the power of the Persian Empire. In 332, he conquered Syria, cutting Egypt off from the Persian capital. He marched his army to the capital Memphis, just south of modern Cairo, where he was welcomed as a liberator from the Persians. From there he proceeded along the western arm of the Nile to the port of Canopus (modern Abu Qir) and then further westward to a coastal village called Rhakotis (Figure 8-2).

Here, legend has it that the ancient Greek poet Homer appeared to Alexander in a dream while he slept near the village and told him to construct a city on that spot. But the potential of the site must have

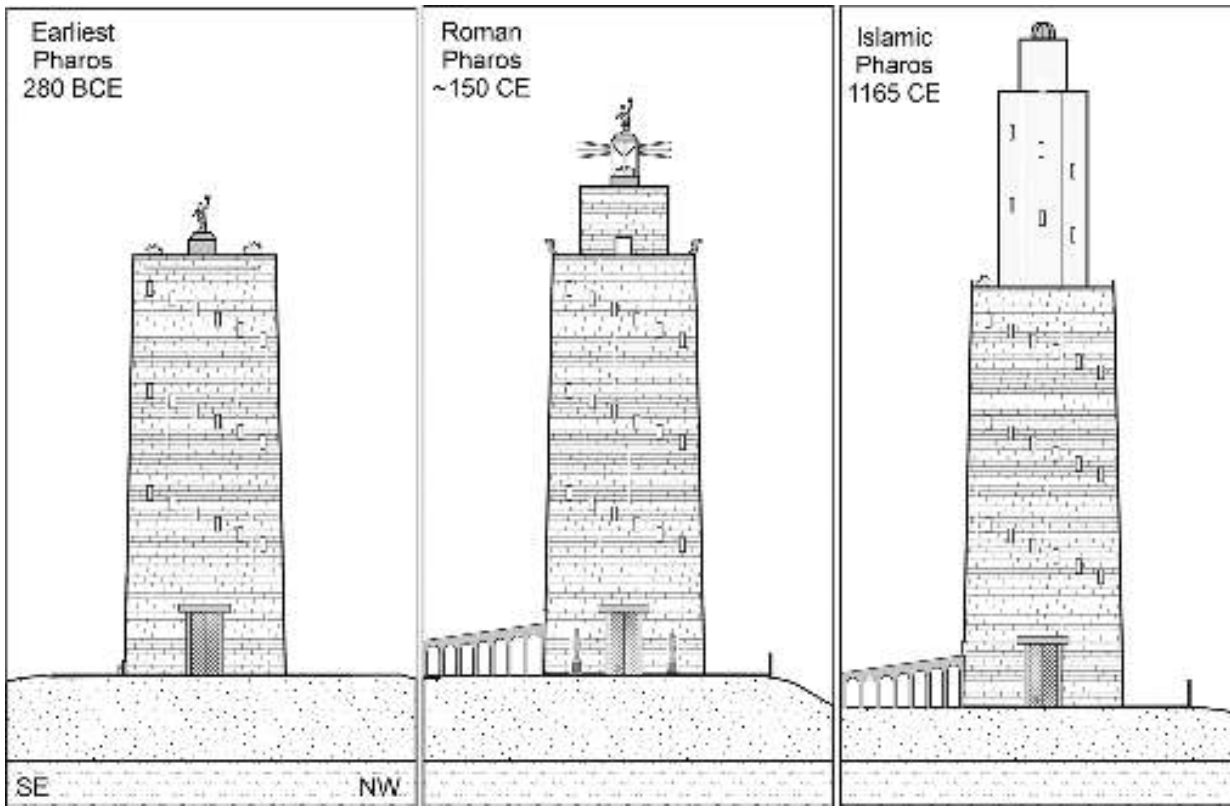


Figure 8-1: The Pharos stood on an island at the entrance to Alexandria's harbour and was reconstructed many times during its 1,500-year history. The earliest Pharos may have been a simple stone tower with a monumental doorway, topped by a statue of Zeus and hearths for occasional signal fires. In Roman times the Pharos had two stories and an improved lighting system involving mirrors. A ramp led to a utility entrance and the surrounding courtyard was set with statues. The Islamic Pharos had a brick octagonal second stage that was topped by a circular mosque with a dome. Signal fires were set on the first platform, as in the original building. It was taller than earlier incarnations but this was partly compensated by five metres of land subsidence, mostly in the eighth–ninth centuries. A tiny figure in front of the door shows the gigantic scale of this building. Image by the author.

been already evident to Alexander: not only was it close enough to the Nile delta to profit from the fishing and farming there, but also lay along a narrow ridge of land that protected it from flooding. Just to the south, Lake Mareotis (now Maryut Lake) linked the site to the Nile, and to the north, the harbour was sheltered from the open sea by Pharos Island ("Seal Island"; Figure 8-5). This harbour had an additional advantage over ports to the east: it was much less susceptible to silting. The annual flood of the Nile deposited sediments around the harbours at Canopus and Damietta making access difficult. Here

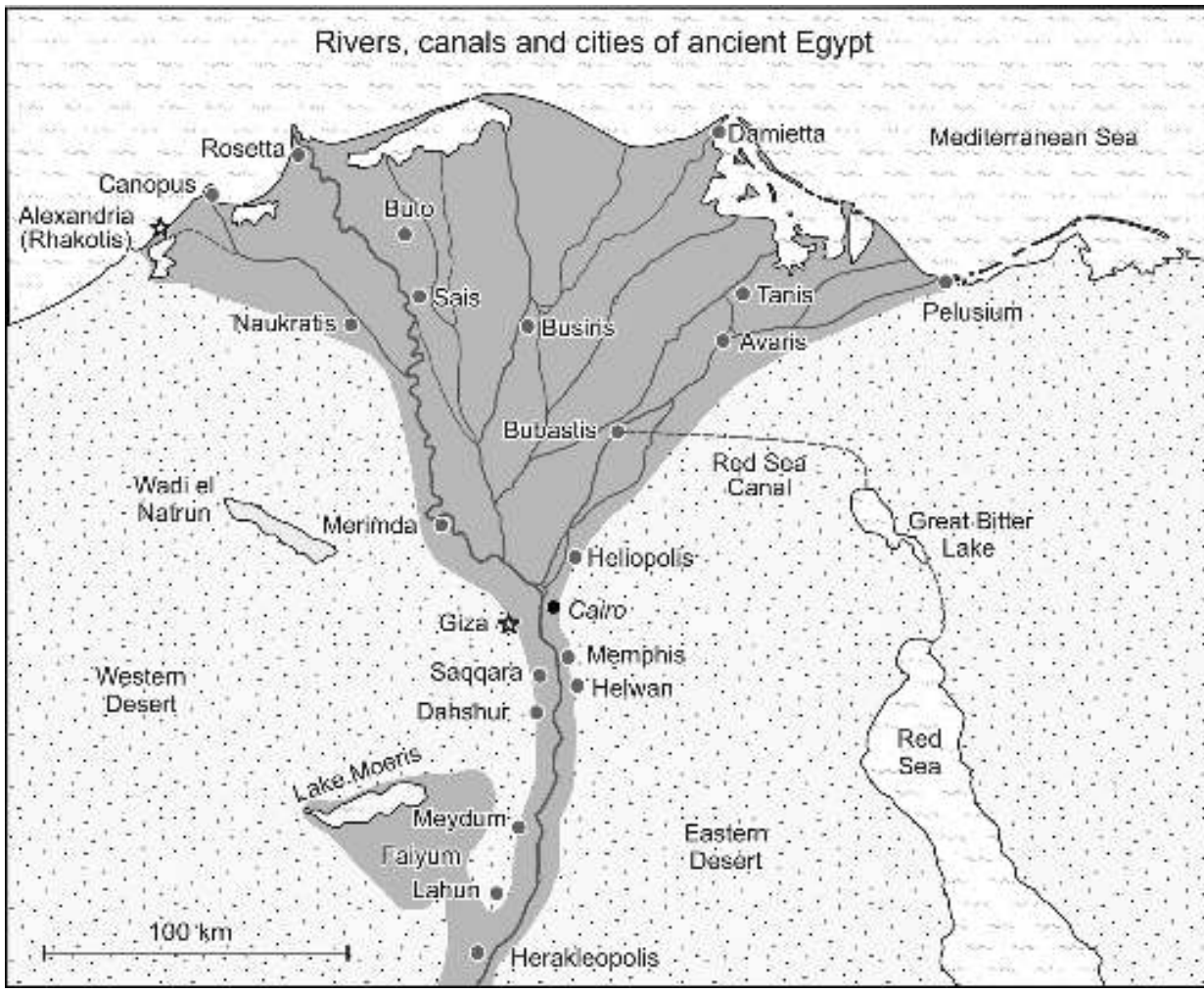


Figure 8-2: The Nile Valley and Delta were the most important parts of ancient Egypt. To the north of Memphis, the ancient capital, the Nile splits into many branches that meander across the flat terrain. The Canopus (western) arm of the Nile, which was so important for the development of Alexandria, is now dry and water flows instead in the Rosetta arm. Map by author after Jeff Dahl / Wikimedia Commons CC BY-SA 4.0 and Cooper, J.P., 2009, "Egypt's Nile-Red Sea Canals: Chronology, Location, Seasonality and Function," in Connected Hinterlands, L. Blue, et al., Editors, Archaeopress. 195–209.

at Rhakotis, however, an eastward current along the coast flowed behind Pharos Island and kept the harbour clear of sediments. All these advantages were balanced by the site's distance from the Nile, making maritime connections to the core of Egypt more difficult (Figure 8-3).[334]

It was here in 331 BCE that Alexander founded his new city, the first of many around the ancient world called Alexandria, and subsequently

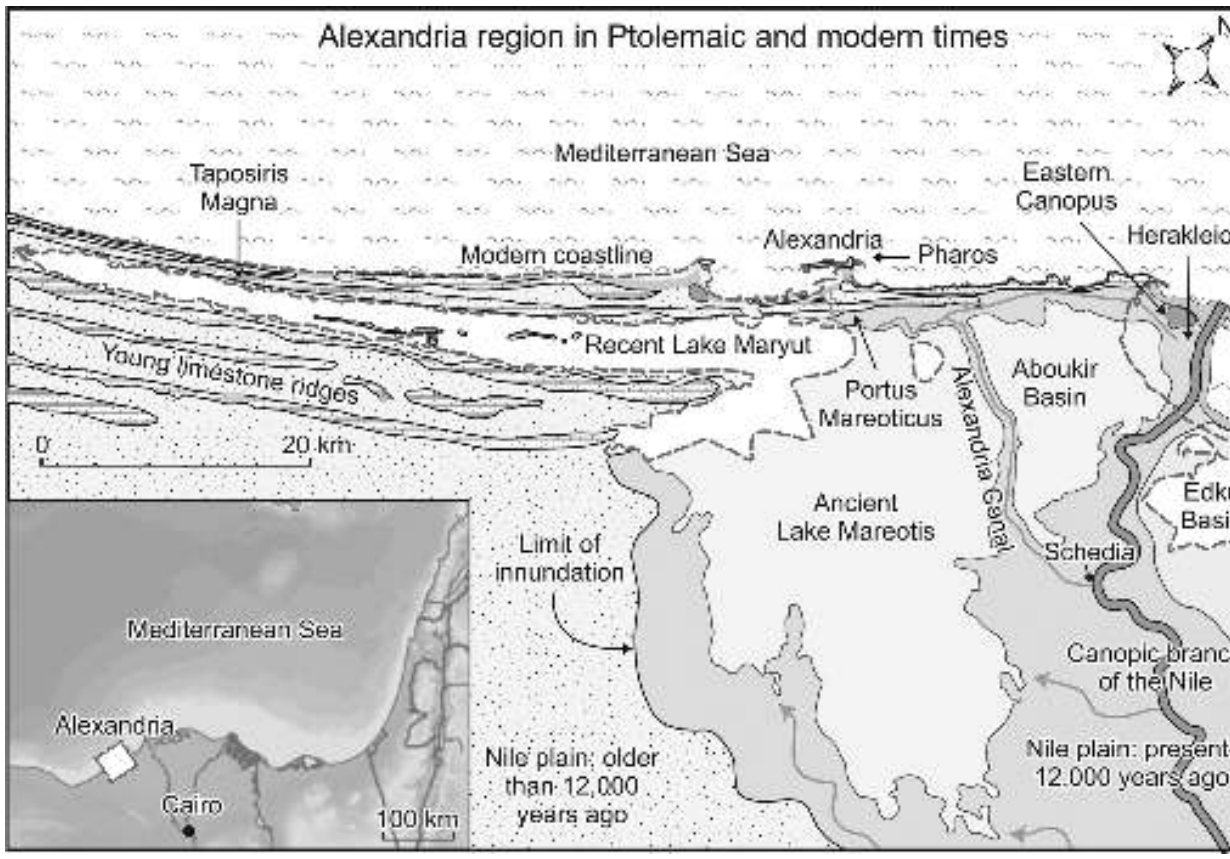


Figure 8-3: Ptolemaic Alexandria had access to both the Mediterranean Sea and Lake Mareotis, which was in turn connected to the Nile by the Alexandria Canal and several smaller canalized streams. The geography has changed considerably since antiquity: Maryut Lake is much smaller than its ancient predecessor, the Canopic branch of the Nile no longer flows and the coastline has retreated over the ancient cities of Canopus and Herakleion. Image by author after Flaux, C., et al., 2021, The late Holocene record of Lake Mareotis, Nile Delta, Egypt. E&G Quaternary Science Journal. 70(1): 93–104.

the greatest. However, long before Alexander arrived. people knew of the harbour behind Pharos Island—Homer mentions it in his epic poem *Odyssey*, first written down five hundred years before the construction of the Pharos: "There is an island called Pharos in the rolling sea off the mouth of the Nile . . . On this island is a sheltered cove where sailors come to draw their water from a well and where they can launch their boats on an even keel into the deep sea." (Odyssey, IV, 351–360.)[335] There is also archaeological evidence for a settlement around 1000 BCE[336] and chemical evidence for even earlier activity. Samples from sediment cores taken from the harbour and lake

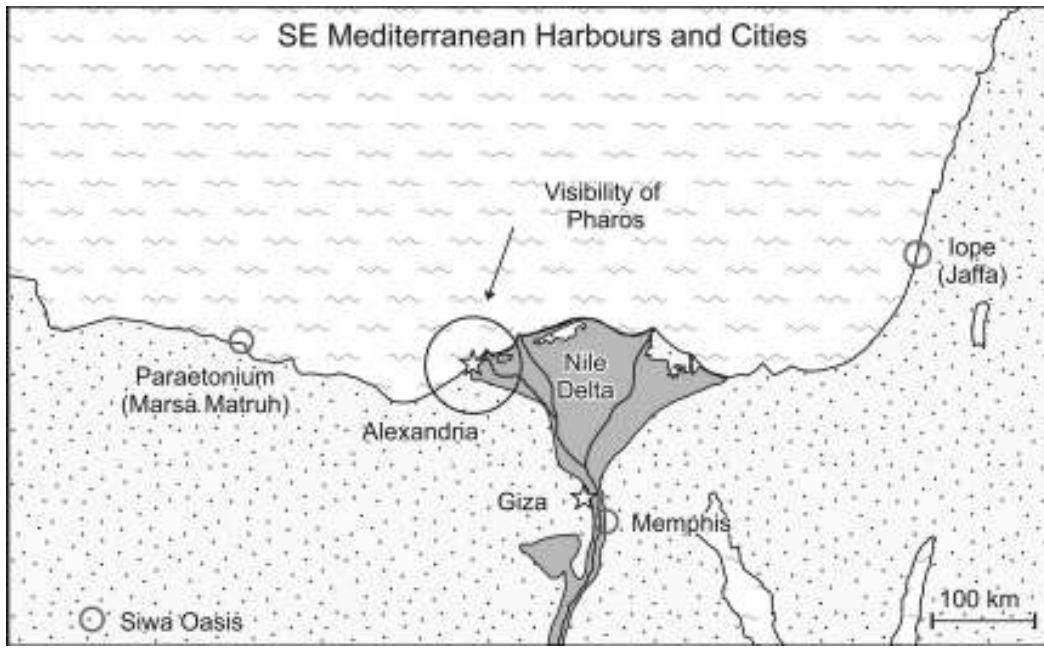


Figure 8-4: The south and southeast coasts of the eastern Mediterranean have little relief, both on land and undersea, making navigation difficult and dangerous. The Pharos was initially just a tower built to guide boats to the only good harbour between Paraetonium and Iope. Map by the author.

have high levels of copper and lead dated at about 3500 BCE. These geochemical anomalies mostly reflect metals naturally occurring in human and animal waste, and indicate the presence of an important settlement at that time.[337] However, we do not know what was going on at Rhakotis in 332 BCE, when Alexander arrived.

This long period of occupation was no doubt due to the quality of the harbour and the lack of alternatives along the coast (Figure 8-4). Some three hundred years after the founding of Alexandria, Diodorus Siculus described the voyage along the coast as: "... exceedingly long, and any landing is especially difficult; for from Paraetonium [now Marsa Matruh] in Libya as far as Iope [now Jaffa] in Coele-Syria, a voyage along the coast of some five thousand stades [900 km], there is not to be found a safe harbour except for Pharos. And, apart from these considerations, a sandbank extends along practically the whole length of Egypt, not discernible to any who approach without previous experience of these waters." (Library of History, 1.31.3, Loeb translation.)

Alexander did not tarry long here and soon continued west to Paraetonium and then south to the Siwa oasis (Figure 8-4; see Chapter 2, Geology of Egypt), where he was acclaimed as the son of Ammon-Re, an Egyptian god conflated with Zeus. He returned directly across the desert to Memphis and, leaving his viceroy Cleomenes in charge, he resumed his war with the Persians. On Alexander's death in 323 BCE, the empire was split up and Egypt was claimed by his friend Ptolemy, who transformed it into the longest lived and most successful of the successor kingdoms, including at its maximum extent Libya, Cyprus, the Middle Eastern coast, and parts of southeast Turkey.[338]

If trade with the new port of Alexandria was to prosper, it needed a tower to guide ships from the Mediterranean Sea to the harbour.[335,339,340] The Pharos may have been the idea of Ptolemy, but it appears to have been designed and financed by Sostratus of Cnidos, a military engineer and friend of the king.[338,341] Construction probably began in 297 BCE and was completed early in the reign of his son, Ptolemy II, who was in power from 283 to 246 BCE.

There were also other major civil engineering works at that time.[343] One project was the *Heptastadion* ("seven stadions" = 1.4 kilometres), a causeway from the mainland to Pharos Island possibly with bridges at either end. This divided the bay into two rather better harbours, but as with many such projects, there was an unforeseen side effect: the eastward coastal current could no longer flow between the island and mainland to flush out sediments deposited from the muddy waters. The channels beneath the bridges may have been intended to reduce this problem, but if they existed, they were inadequate: subsequent accumulation of silt and sand on either side of the causeway converted it into a broad spit of land that central Alexandria now occupies.[342]

Ptolemy also ordered the construction and renovation of canals. The *Alexandria (Schedia) Canal* connected the city with Upper Egypt through the Canopic branch of the Nile (Figure 8-3). This route largely bypassed Lake Mareotis, which was too shallow in places for the passage of larger boats. Although it silted up quite fast and required regular dredging, it was easier to maintain than a route through

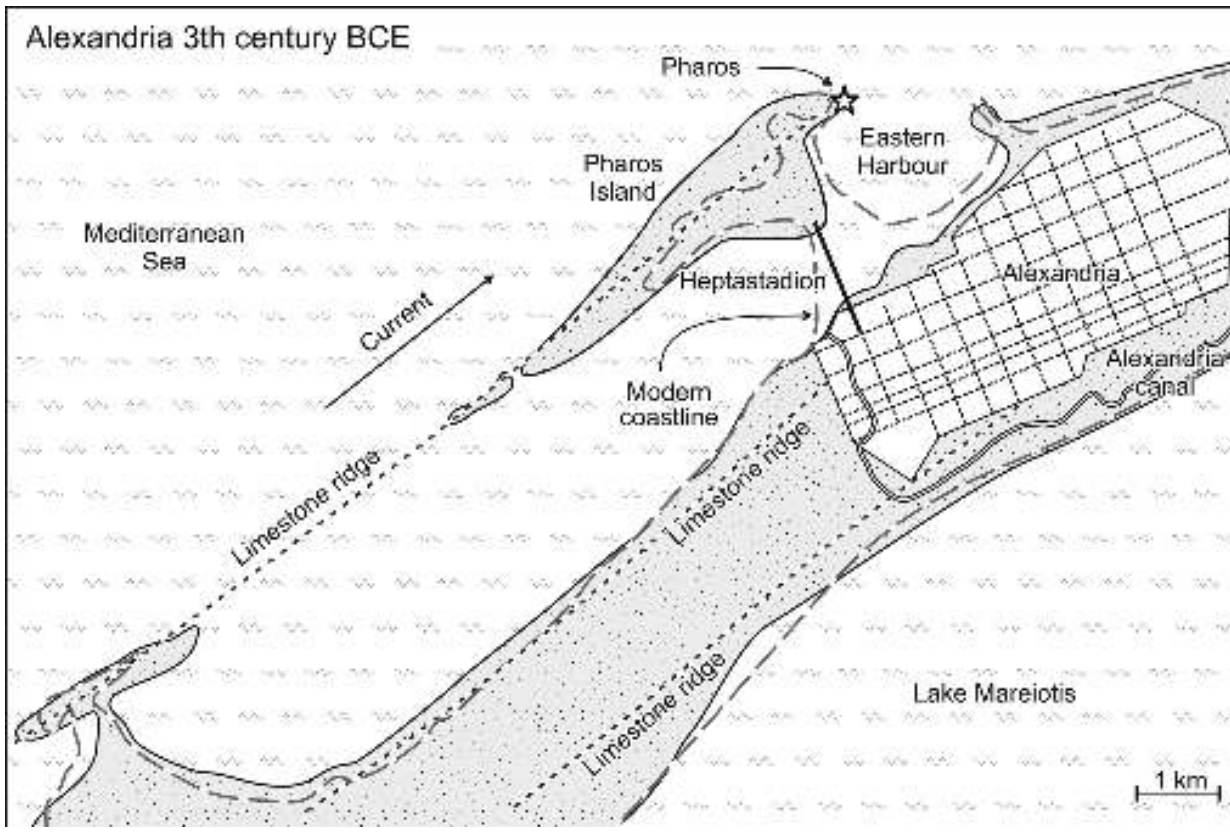


Figure 8-5: The Pharos was built close to the northeast tip of Pharos Island, one of the many discontinuous limestone ridges typical of the area. The Heptastadion, a causeway with two bridges, linked the island to the mainland and made the Eastern Harbour. The local geography has changed since antiquity partly because the land has sunk five metres, reducing considerably the size of Pharos Island, and also because of the development of a wide sand-spit on either side of the causeway. Map by author after Flaux, C., et al., 2021, The late Holocene record of Lake Mareotis, Nile Delta, Egypt. E&G Quaternary Science Journal. 70(1): 93-104; Marriner, N., J.P. Goiran, and C. Morhange, 2008, Alexander the Great's tombolos at Tyre and Alexandria, eastern Mediterranean. Geomorphology. 100(3–4): 377-400; McKenzie, J., 2007, The architecture of Alexandria and Egypt, c. 300 B.C. to A.D. 700. Yale University Press: New Haven, Conn.

the lake (see box 6-7: Dredging Techniques). The canal also brought water to the city along aqueducts that ran under the streets and along the causeway to Pharos Island. These aqueducts were most active when the Nile was in flood when they were used to fill cisterns.[343] Another canal linked the Delta to the Red Sea (Figure 8-2), following a former branch of the Nile that once flowed into the Red Sea. This link opened up maritime trade to the south and east, meaning that Alexandria was truly at the crossroads of the Mediterranean.[333]

After Rome conquered Egypt in 31 BCE, Alexandria flourished. Portus Mareoticus was built beside the lake to accommodate traffic along the canal from the Delta as well as industrial products from around the lake (Figure 8-3).[344] These goods were transhipped across the city and exported from the northern harbours. Dredging of the canal increased water flow from the Nile so that the level of the lake was raised, reducing seasonal incursions of the sea into the lagoon to the east of the city that made the waters brackish and less productive.

Political changes following the departure of the Romans and their insatiable demand for food grains reduced the importance of the ports so that the lakeside facilities were largely abandoned by the 7th century.[344] These effects were later compounded by geographical changes: regional tilting of the land, or perhaps inundation of wind-borne sediments from the desert, may have been responsible for reducing the flow in the Canopic branch of the Nile to the profit of the Rosetta branch to the east. Although the Alexandria canal may have continued to exist, the flow was much lower and by the 9th century most of Lake Mareotis had dried out leaving behind an inhospitable, sandy basin. It was only under the Ottomans that the fortunes of the city turned and this vitality continues to the present day, with the result that little of ancient Alexandria has been excavated, although its remains are thought to be well preserved 10–12 metres below the surface.

The Pharos existed for 1,500 years and was rebuilt many times, so it is impossible to create a single, definitive image of the building, although many have tried. The lower part may have been somewhat constant over the years, but the upper parts were more vulnerable to earthquakes and were reconstructed in different styles. Here, I try to establish what it looked like at three different times (Figure 8-1).

We have no images of the earliest Pharos, just an epigram by Posidippus of Pella, probably written shortly after the building was completed, which may have been inscribed on the base of the structure. It mentions "this tower, in a straight and upright line, appears to cleave the sky from countless stadia away, during the day, but

throughout the night quickly a sailor on the waves will see a great fire blazing from its summit . . . and not miss Zeus the Saviour." This passage suggests that the Pharos was a simple tower with a platform at the top bearing a statue of Zeus and hearths for signalling (Figure 8-1). Lighting such fires must have been an exceptional event as sailing at night was avoided in the 3rd century BCE.[345]

The lower section of the Roman and Islamic Pharos was likely the entire original tower.[346] A 12th century CE manuscript reveals that this section was 77 metres high with a width tapering from 30 metres at the base to 26 metres at the top. Simple geometric forms were favoured by the Egyptians and this tower resembles the gateways ("pylons") of some temples, such as at Luxor in southern Egypt (Plate 14b). In a way, the Pharos could be considered to be the gateway to Alexandria's harbour. A huge granite doorway stood at the base facing the harbour (Plate 15a). It seems unlikely that this frame housed doors that could be opened, so it may have been more like the "false" doors of ancient tombs. The actual entrance must have been on another face of the structure.

We know something about the Roman Pharos from sparse documents and coins (Figure 8-1). Strabo, visiting in 26–20 BCE, mentioned that the Pharos was built of white stone and had several stories. More direct information can be had from Roman coins (Figure 8-6). The platform at the top of the first story had statues of Tritons, possibly shown as mermen, and hosted a second, narrower story about a quarter the height of the first story. At the top, a series of columns supported a statue of Zeus, perhaps the same as that which topped the earliest Pharos. A long ramp led to an entrance high up on one side.

It was in Roman times that a permanent light was added: trade had increased so much that congestion may have required dusk or night sailing, as was done at other major ports in the empire. We really have no clear idea of how the light was produced but one possibility is that light from a fire in the base of the tower was reflected out to sea by huge mirrors of polished bronze placed at the top of the building. The solution favoured here is that a hearth under the Zeus statue

Figure 8-6: Roman coins minted in Alexandria are the earliest representations of the Pharos. These coins show that the first storey had a monumental door (right), windows (dots) and a terrace with projecting statues. The next storey was narrower and terminated in a cupola topped by a large statue of Zeus Soter ('saviour'). Public Domain / Wikimedia Commons CC BY-SA 3.0.

held a fire whose light was reflected by mirrors just beneath the statue (Figure 8-1). The exterior ramp may have been constructed to ease transport of fuel for the fires.

We have much more information on the Islamic Pharos as Alexandria was an important waystation on the way to Mecca and many 10th–14th-century pilgrims recorded their observations[346] (Plate 15b). Some of these accounts mention that the Pharos was damaged by earthquakes and restored several times. The best description comes to us from *al-Balawī* of Málaga, an architect and builder, no doubt with a professional interest in the Pharos, who visited in 1165 CE and measured it carefully (see box 8-1: Ancient Units of Length and Distance) (Figure 8-1).

"The Pharos rises at the end of the island. The building is square, about 45 steps wide on each side. The sea surrounds the Pharos except on the east and south sides. This platform [courtyard?] measures, along

Box 8-1 Ancient Units of Length, Distance, and Weight

Metrology, the discipline of measurement, is at the core of science, both now and in antiquity. So how were such measurements done in the past and what units did they use?

Most, or perhaps all, ancient length units were derived from the human body.[380] Of course, bodies vary considerably by the size, but it is safe to assume that the base was a well-fed adult male, which reduces variability somewhat. Commonly, multiple units were used depending on practical considerations such as what was being measured, width, height, or length of a cord used for measurement, and the size of the object. For instance, in 1166 CE *al-Balawī* used five different units to describe the Pharos.[346]

The smallest hand unit was the width of the thumb, now called the inch (~2.5 centimetres). Other hand-based units were the width of the palm (~8 centimetres) or hand, as well as the span, which was the distance from the tip of the small finger to the tip of the thumb of an outstretched hand (~20 centimetres). The span was easy to use for measurements as you can rotate the hand around the thumb and little fingertip. The most commonly used smaller unit was probably the cubit (~45 centimetres), the distance from the bottom of the elbow to the fingertips. This unit seems to have been widespread in the ancient world with local attempts at standardization. In Dynastic Egypt, the fundamental unit appears to have been the Royal Cubit, which was equal to a regular cubit plus a palm (~53 centimetres). The fathom (183–200 centimetres) was the distance between the ends of the fingers with the arms outstretched. It was a convenient unit for measuring the length of a cord used to determine water depths or building heights.

Horizontal distances were most easily measured using the foot (29–32 centimetres), step (~75 centimetres) or pace (~150 centimetres). Larger units were the *plethron,* which was 100 Greek feet (30 metres), the *stadion*, which was 600 Greek feet or 120 paces (~189–200 metres), and the *Roman Mile* which was a thousand paces (~1500 metres). In ancient Greece and Egypt, specialists

determined distances for military or civilian purposes by pace counting and the Romans used a wheel-based measuring devic.[381] Comparisons with modern measurements show that such methods were accurate to a few percent.

One of the earliest measures of weight, in Egypt, was the *mina* which weighted ~0.5 kilograms and was close to a modern pound. The physical basis of this unit is unclear, but I think that it may have been the weight of a cube of water with a side the width of the palm (~8 centimetres). The mina was commonly divided into 60 *shekels*. The *talent* was commonly 60 minas and weighted ~30 kilograms: we have come across in the discussion of the amount of metal used to make the Colossus (see Chapter 7). Minas and shekels were also units of currency, probably initially a weight of silver.

You may have noticed that a factor of sixty occurs in several contexts. Sixty occurs in the subdivisions of talents and minas. The stadion was 60 × 10 feet. There are other instances that I have not yet mentioned: 60 × 6 degrees in a circle, 60 minutes in a degree or hour, and 60 seconds in a minute. The importance of sixty was inherited from the Babylonians whose mathematics was based on factors of sixty and ten. So why sixty? We rationalize our decimal system by counting our ten fingers sequentially, but there is no reason why human-based digital systems of numbers have to be so restricted, and the use of base sixty may be a good example. It may have been a simple matter of counting each of the three phalanges of the four fingers of one hand (3 × 4 = 12) with each of the five digits of the other hand for a grand total of sixty (12 × 5 = 60).

its sides, from the tip, down to the foot of the Pharos walls, 12 cubits [6 m] in height. However, on the side facing the sea, it is larger because of the construction and is steeply inclined like the side of a mountain. As the height of the platform increases towards the walls of the Pharos its width narrows until it arrives at the measurements above. . . The doorway to the Pharos is high up. A ramp about 100 steps [68 m] long used to lead up to it. This ramp rests on a series of curved arches; my companion got beneath one of the arches and stretched out his arms

but he was not able to reach the sides. There are 16 of these arches, each gradually getting higher until the doorway is reached, the last one being especially high."[335,346]

"Eventually, . . . we reached the first stage [of the Pharos]. There was no stairway [inside] but a ramp that gradually ascended around the cylindrical core of this huge building. . . . We entered a corridor 7 hand-spans wide overhung with finished stones that formed a ceiling. . . . When we arrived at the top of the first stage we measured its height from the ground with a piece of string from which we hung a stone—it was 31 fathoms [77 m or perhaps 62 m]; the parapet being about a fathom high. In the middle of the platform of this first stage, the building continued upwards, but now in the shape of an octagon with each face ten steps long and 15 spans from the parapet. The wall was about one fathom thick; the figure which I had written down in my original notes is not very clear, but close by where I had recorded the length of the string I had written details in ink, which had not smudged. This is most strange . . . but I am sure it was a fathom. This stage was taller than its baseline. Entering we found a staircase which we counted as having 18 steps and arrived at the middle of the upper floor. We measured again with the string and found that it was 15 fathoms above the first stage. In the centre of this platform on top of the second stage, the building continued upwards in cylindrical form with a diameter of 40 steps. . . . We entered again and climbed 31 steps to arrive at the third stage. The height of the third stage was measured with the string as 5 fathoms. On the platform of the third stage, there is a mosque built with four doors and a cupola. It is 3 fathoms high and 20 steps in diameter. . . . In summary, the structure that we had explored had 67 rooms, except for the first which we found closed and which, it was said, led underground to the sea." (Unit conversions from.[346])

Other details of the Pharos are recorded in the Islamic descriptions. At the top of the first section, there was an inscription written in *images*, possibly hieroglyphics, 50 centimetres high. The upper stages were made of brick and there was a light on the Pharos, possibly on

the first platform. These descriptions have been used to establish the form of the Pharos in the 12th century (Figure 8-1).[346] They have, unfortunately, also been used in the popular imagination to define the Pharos in Ptolemaic and Roman times.

Parts of *al-Balawī's* description are unclear, but it is the best that we have. Luckily, we can complement his work by looking at the physical remains of the Pharos that have been recently rediscovered on the seafloor (Figure 8-7).[347,348] The position of the Pharos on a small, relatively isolated island meant that after it fell it was difficult to scavenge the blocks for other construction projects, although some material was immediately recycled to build a small tower and subsequently a mediaeval fort.

Most of the blocks on the harbour floor and in the fort—which must have been the walls of the Pharos—are made of a shelly limestone called coquina (see Chapter 7), which occurs elsewhere on the former island. The ancient quarries, however, have not been found since they are probably underwater—remember that the land has sunk five metres since that time (Figure 8-5). I'll discuss the origin of the island later, but briefly, these rocks were formed by natural cementation of shelly sand. This porous, poorly cemented limestone was easily cut using stone tools and bronze saws. However, it was also easily eroded by sea spray: crystallization of salt just beneath the surface would have caused the rock to flake, meaning that the Pharos must have needed frequent repairs, especially at its base near sea level.

There is also an assortment of other materials both on the harbour floor and in the fort. Seven large blocks of Aswan granite (see Chapter 2: Pyramids) are from the monumental doorframe of the Pharos, which stood almost 13 metres high and was shown on Roman coins (Figure 8-6, Figure 8-7). The lintel is still almost in place, so the doorframe must have been at the base of the structure.

There are also many statue fragments made of Aswan granite and Gebel Ahmar quartz-rich sandstone.[349] These statues predate the Pharos and were moved down the Nile from temples elsewhere in Egypt during Ptolemaic or Roman times. Column shafts, bases and

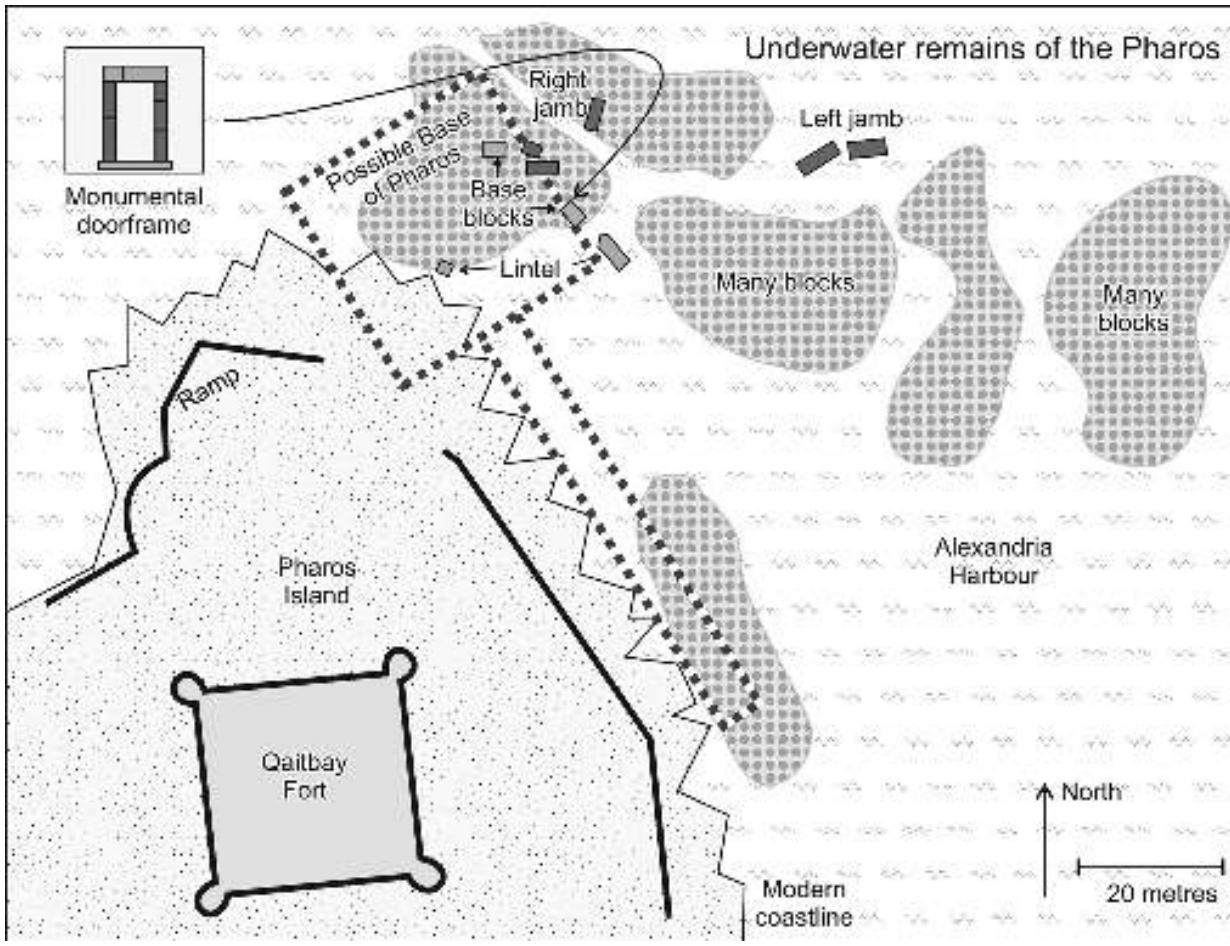


Figure 8-7: Over three thousand blocks lie on the harbour floor northeast of Qaitbay Fort. Most are from the walls of the Pharos, together with parts of the granite frame of the monumental door thirteen metres high that faced to the northeast. There are also column drums, bases, and capitals, as well as statues, sphinxes, and obelisks, which may have stood in the courtyard around the Pharos or in an adjacent temple of Isis. Most of the area covered by this map was probably dry land when the Pharos was built. Map by author after Hairy, I., 2006, "Le phare d'Alexandrie, concentré de géométrie." *La Recherche* (394): 44–50; Hairy, I., 2020, "The Qaitbay Underwater Site at Alexandria, Egypt: The Evolution of Surveying Techniques," in Under the Mediterranean: The Honor Frost Foundation Conference on Mediterranean Maritime Archaeology.

capitals, sphinxes and obelisks may have been from the courtyard surrounding the Pharos, or adjacent buildings. About fifty blocks and statues have been recovered from the seafloor and are currently exhibited around Alexandria.

The development and wealth of Alexandria were firmly linked to the Nile. This great river, the longest in the world, channelled goods to and from the port. Its waters made the Delta the most agriculturally

productive part of the ancient Mediterranean world. Herodotus expressed this well in the 5th century BCE: "For it is clear to any intelligent observer . . . that Egypt . . . is, as it were, the gift of the river and has come only recently into the possession of its inhabitants."[53] But what do we know of this river and its long history?

The Nile

The story of the Nile starts twenty million years ago when plate tectonic movements began to tear the African-Arabian continent in two.[350] This rifting process never went far enough to create a new ocean but was sufficient to make the Red Sea and the great rift valleys that still dominate the landscape of east and central Africa.[351] Here, as elsewhere, the land on either side of the rift was uplifted, forming chains of mountains. Water flowed from this region into Sudan and thence intermittently in shallow meandering rivers to the Mediterranean Sea. The course of the river was constrained to the east by the Red Sea Mountains. To the west, the land rose slightly but did not make such an important or permanent barrier.

The geography of the Nile valley did not change significantly until six million years when tectonic forces—the convergence of Africa and Europe—reduced the depth of the Gibraltar Strait, eventually

Figure 8-8: The ancient name of the Nile is written here in hieroglyphs: from left to right, top to bottom, the symbols are transcribed as the letters i t r w and the wavy lines on the right are a symbol for water that was used to clarify the meaning. We now pronounce this name *Iteru* but do not know how it sounded in ancient times, as vowels were not normally shown. The word Nile is derived from the ancient Greek name of the river, but the origin of that name is unclear. Image by KES47 / Wikimedia Commons, CC BY-SA 3.0.

isolating the Mediterranean Sea from the Atlantic Ocean. Evaporation from this closed basin soon transformed the Mediterranean into a vast desert with salt lakes as much as four thousand metres below sea level, ten times greater than the present Dead Sea.[19,352,353]

This new geography changed the Nile valley drastically. Although the height of its source in the highlands of central Africa was unchanged, the river now debouched into a saline lake far below sea level. With a far steeper descent to the sea, the river ran faster and rapidly eroded its valley, finally gouging out a canyon 10–20 kilometres wide and up to 2,500 metres deep. At Aswan, 1,300 kilometres from the mouth of the river, the canyon was still an impressive 170 metres deep. The numerous wadis (dry valleys) that connect the Nile valley to the Eastern and Western Deserts were produced at this time.

The Nile continued its steep descent into the sea lakes of the Mediterranean Basin for three hundred thousand years until the barrier at Gibraltar was breached, allowing water from the Atlantic to flow once again into the Mediterranean Basin. The whole process may have taken less than a year with the sea level rising ten metres a day.[354] The Nile Canyon was suddenly transformed into a deep marine embayment more than 1,300 kilometres long. Sand and mud transported by the Nile were now deposited at the head of the bay near Aswan, burying the canyon. As sedimentation continued, the mouth of the river advanced to the north, finally filling the whole Nile valley and the wadis almost to the top leaving only a line of low cliffs.[351]

The buried canyon at Aswan was only discovered when the modern dam was built and measures had to be taken to prevent water leaking through the sediments under the dam. The Nile Canyon was comparable in width and depth to the Grand Canyon in the USA, but four times as long.

The Nile started to follow its modern route a few million years ago and since then its flow has been modulated by the great climatic cycles of our present Ice Age (Figure 8-13). These, in turn, were controlled by cyclic changes in the orbit of the Earth around the Sun, also known as the Milankovitch Cycles. Fifteen thousand years ago,

orbital changes caused the zone of monsoon rains to move northwards and the Sahara became a region of woodlands, grasslands, and lakes, rather like the present-day Sahel region, with hippos, giraffes, and elephants.[40] Eight thousand years ago, hunter-gatherers moved into the "Green Sahara" and were followed later by cattle herders. This community survived until 5,500 years ago, when orbital changes caused the monsoon zone to move to the south, transforming the Sahara into the desert that we see today. It used to be thought that human over-exploitation had caused desertification, but it appears that it was simply climatic, and pastoralism may have actually delayed the onset of the desert by a few hundred years, perhaps by enhanced care of pastures.[355] Human habitation followed these climatic changes: the population of the Sahara moved southwards to central Africa, then eastwards to the Nile headwaters and finally northward to the Delta. Here, people flourished as they learned to live with the Nile's unusual flow cycle.

The modern Nile is fed from three main sources: The White Nile, named for the relative clarity of the water, and the Blue Nile and the Atbarah River, which are full of clay and sand (Figure 8-9, Figure 8-10).[351] The waters of the White Nile come from equatorial Africa and are relatively constant throughout the year. The rocks there are old, hard metamorphic rocks that do not weather easily and thus provide little sediment. The Blue Nile and the Atbarah River rise in the highlands of Ethiopia, where the monsoon rains make for huge variations in flow. The rocks there are geologically young volcanic rocks, which have weathered to clay in the hot and humid tropical climate. It was this source that caused the annual flooding of the river during the summer and early autumn, and brought down the sediments that fertilized the Nile valley and Delta.

The annual cycle of the Nile flood greatly influenced the nature of the crops that could be grown in Egypt (Figure 8-10).[351] Planting had to be done in the winter during the season of Peret for harvest in Shemu, before the season of Akhet when the level of the Nile rose by as much as seven metres, covering the adjacent lowlands with water

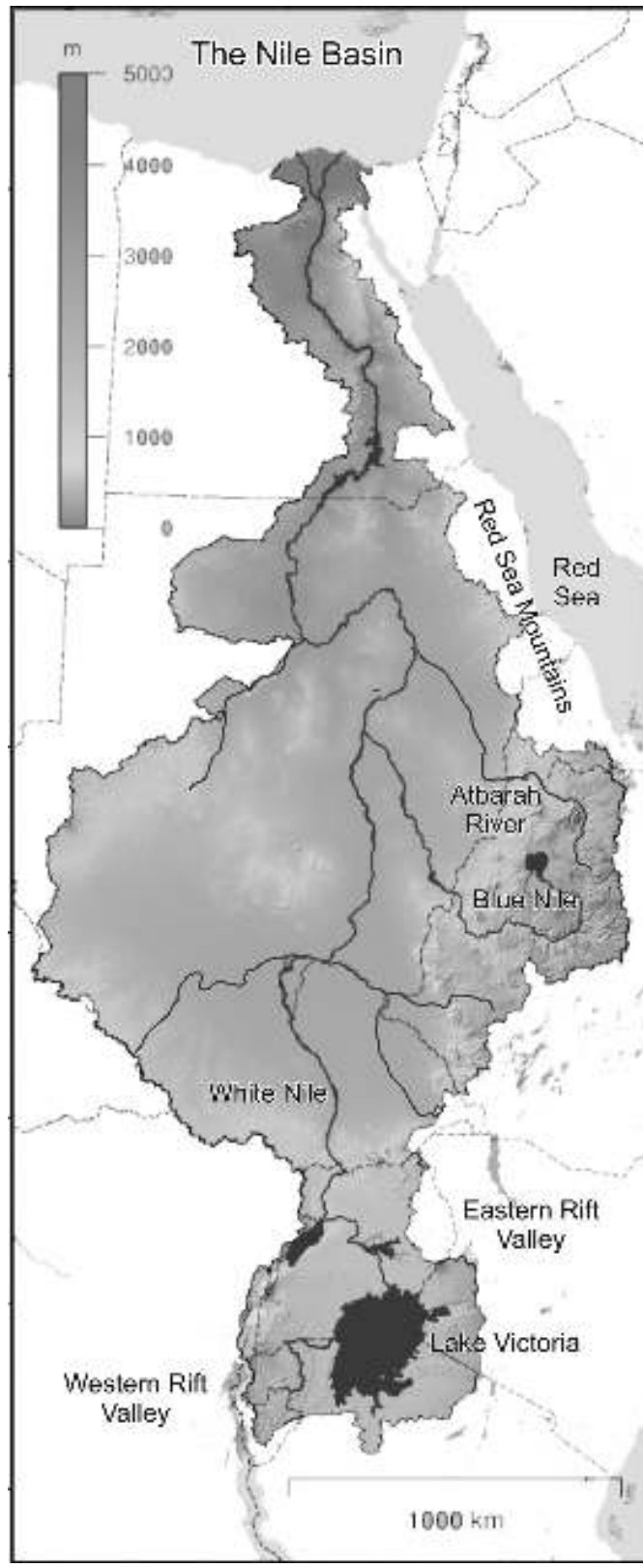


Figure 8-9: The Nile River basin extends from the Mediterranean Sea southwards for over three thousand kilometres. The muddy waters of the Blue Nile and Atbarah River come from the highlands of western Ethiopia, whereas the clearer waters of the White Nile originate around Lake Victoria. Image by the author after Wikimedia commons, public domain.

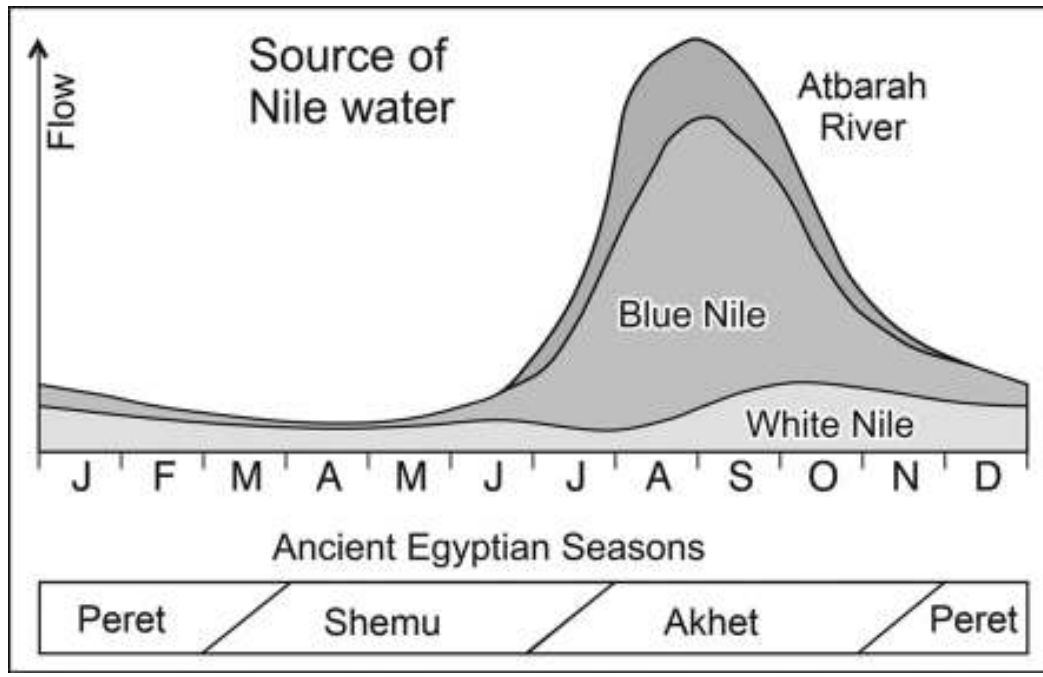


Figure 8-10: The different water and sediment sources that feed the Nile create its unusual annual cycle. The calendar was divided into three four-month seasons with the start of the year determined from lunar and stellar observations. Image by author after Woodward, J.C. et al., 2008, The Nile: Evolution, Quaternary River Environments and Material Fluxes, in *Large Rivers*, A. Gupta, editor, John Wiley & Sons, Ltd., 261–292.

and life-giving mud (see Chapter 2: Pyramids). The actual start of flooding depended on the year and position in the Nile valley—the peak of the flood moved northwards with time. The Akhet season was when it was easiest to transport stone and other goods by water.

The unusual cycle of the Nile meant that farming was done in the winter and that the food plants cultivated in ancient Egypt, such as broad beans, lentils, onions, leeks, barley, and wheat, are ones we associate with cooler climates. Indeed, during Roman times the Delta produced so much wheat that it was known as the *Granary of the Empire*. Construction of the dams at Aswan eliminated the annual flooding, enabling the cultivation of warm-weather crops as well, but not without serious side effects that I will discuss later.

The magnitude of the yearly Nile flood was never constant, and variations had tremendous implications for the economy and political stability of Egypt. With this in mind, measuring stations (Figure 8-11)

Figure 8-11: *Nilometers* were used to measure the height of the Nile flood and its date, which were important for planning water distribution and estimating agricultural yield for tax collection, which was paid in kind. This rather modest example is at Aswan and was connected to the river by the small tunnel seen in the lower right corner. Photo courtesy of the author.

were set up to record the highest level of the flood each year and functioned from antiquity until 1902 CE when the Nile was first dammed at Aswan. There are gaps in the written documentation, especially during times of conflict, but geological records can sometimes fill in missing information (see box 1-3: Getting Information on Ancient Climates). During each flood, lagoons in the Delta were filled with muddy water, which then settled out to the bottom. The composition and thickness of each mud layer inform us about the magnitude of the annual flood.[356] More information comes from another, somewhat unlikely source: the teeth and bones of mummies.[357]

These people ate plants and animals that were nourished by the Nile, so their bones preserve some characteristics of the river water. The isotopic compositions of the bones can tell us about the east

African monsoons from which we can get information on the Nile floods. Indirect evidence of the magnitude of the floods can also be had from documents such as priestly decrees—including the famous Rosetta Stone—and records of land sales and internal revolts.[358] All these data show that stable periods, which made possible the construction of such Wonders as the Pyramids during the Old Kingdom and the Pharos during the Ptolemaic dynasty, may have been ended by social unrest triggered by weak floods and ensuing famine[358] (see box 8-2: Nile Floods and Distant Volcanic Eruptions).

Although Egypt is now known for the ancient cities and monuments of the Nile valley—the Pyramids, for example—the most economically important part of the country has always been the Delta. So how did this region develop?

Box 8-2 Nile Floods and Distant Volcanic Eruptions

The amount of water that inundated Egypt during the annual floods was controlled by the intensity of the monsoon rains in eastern Africa, which was in turn partly linked to global volcanism: major volcanic eruptions inject vast quantities of sulphur into the atmosphere, which is oxidized to sulphate particles that block sunlight and reduce monsoon rainfall.[358] A good record of globally important volcanic eruptions is preserved as layers of ash and sulphates in the ice that is laid down each year in Greenland and this can be correlated to the height of the Nile floods from other records.

A major eruption may well have destabilized the Ptolemaic dynasty in 30 BCE and contributed to the defeat and death of Cleopatra. Egypt had been enfeebled during much of her reign by the weakness of the Nile floods, which made the population hungry and restive. The reduced flow of the Nile at that time may have been related to an eruption of Okmok Volcano, Alaska, in 43 BCE.[382] This may have been the largest in the northern hemisphere during the past 2,500 years and initiated a decade of cooler weather.

The Delta: Alexandria's Hinterland

The Nile delta is the youngest and most geologically variable part of Egypt. Its earlier history—the Mediterranean desert and subsequent refilling—was erased by later events and the modern story started just twenty thousand years ago, during the coldest part of the last glacial period (Figure 8-13). At that time, the Nile flowed through a shallow canyon just north of Cairo, from where it dropped directly into the Mediterranean Sea, then 120 metres lower than now. Multiple channels (distributaries) of the Nile eroded valleys into the soft sediments leaving behind flat-topped hills. With the warming climate, glaciers melted and sea level rose, finally stabilizing near its current level seven thousand years ago. At that time the Delta was a wide zone of shallow interconnected channels interspersed with sandy highlands, the remnants of the former, pre-glacial surface, that provided ideal retreats for animals and humans during the annual inundation of the Delta.[40] This ecologically rich, stable environment enabled the earliest cultural developments in Egypt.[359] Elsewhere, in Europe, for example, this time of environmental stability foreshadowed the end of the Neolithic and the transition to the Bronze Age (see Chapter 6 box 6-6: Sea Level and Cultural Developments).

The modern delta starts just north of Cairo, where the Nile splits into distributaries that fan out until they reach the Mediterranean Sea, making a huge, flat triangle of waterways and wetlands. This characteristic shape has been known for a long time—in the 5th century BCE, Herodotus noted the resemblance to the Greek letter Delta. The river spreads out because the slope of its bed is so shallow that there is little force to keep the water in one channel. The distributaries move across the plain by meandering and breaching of levees, meaning that the ancient geography is not exactly what we see today. The most stable part of the Delta was the apex from which the distributaries divided and this is where some of the largest cities grew up, first Memphis and subsequently Cairo.[40]

The Delta is mostly made of sediments, mud, and sand, transported from equatorial Africa by the Nile—over 200 million tons a year until the recent construction of dams, such as those at Aswan (see box 8-3: The Modern Delta). Formerly, much of the sediment was deposited in the Delta when the waters of the distributaries overflowed into the adjoining basins by avulsions or during the annual flood. Of course, deposition varied from place to place, but over time the whole area was covered with new sediments, about 1 millimetre per year. There was a balance between the addition of new sediments and subsidence so that the overall height of the land stayed close to sea level. The remaining sediments were transported to the coast, where onshore fair-weather waves and coast-parallel currents formed offshore bars, which were a major hindrance to coastal navigation, and sandy berms along the beaches. The rest went into deeper water to make a huge apron of sediments that stretches far into the Mediterranean Sea.

Although Alexandria is close to the Delta, its local geography is quite different and is dominated by a series of low ridges parallel to the coast (Figure 8-3). The Pharos and Alexandria were built on portions of two or three ridges that started to form about seventy thousand years ago.[360,361] There are other, parallel ridges to the south that are progressively older and higher: the last one is a million years old and rises to 120 metres. The ridges are made of coquina (shelly) and oolitic limestone, the source rock for the building of the Pharos. The loosely cemented, granular nature of this rock had led people to call it sandstone: while this is correct, it is better to refer to it as limestone to distinguish it from the far more common types of sandstone that are made of quartz grains. The intervening depressions are filled with carbonate mud and gypsum that formed in shallow, muddy lagoons.

These ridges were an ideal location for construction as they were dry, even during the annual inundation. In addition, the rock was easily cut and strong enough to support buildings. Finally, the rock is porous, so that winter rains can permeate and be accessed during the summer by wells, as Homer mentioned in the Odyssey, quoted earlier. So how did these culturally important ridges form?

Box 8-3 The Modern Delta

The modern Delta is changing fast under the impact of human activities, and much of the northern part is now below sea level, including the remnants of Maryut Lake, which is maintained at 2.8 metres below sea level by continuous pumping (Plate 16b).[383,384] Widespread damage to the Delta started 150 years ago and has been accelerating ever since for several reasons. Its surface naturally subsides by a few millimetres each year when water seeps out from between the grains of sediment, thus reducing the volume of the rock. In addition to this, the weight of the new sediments causes the underlying rocks to sink into the earth. Formerly, these effects were balanced by the addition of more sediments deposited during the annual Nile flood, but now the mud and sand get caught in reservoirs, such as that behind the Aswan dam far to the south.[351] The amount of sediment supplied to the Delta is reduced further by the diversion of water into the 10,000 kilometres of irrigation canals. Sediments are deposited in the canals and are rarely spread out over the former floodplains, preventing the replenishment of natural fertilizers. In addition, in some years no water reaches the sea and pollution is no longer flushed out. Excessive pumping of groundwater has caused incursion of seawater into wells up to 30 kilometres from the coast as well as producing further subsidence by removal of water from the deeper sediments. The problems of the Delta are compounded by a global rise in sea level of about 3 millimetres per year, due to the melting of glaciers and the expansion of seawater as it warms.[385] Clearly, expensive civil engineering projects will be necessary to restore it.[386] A good start would be to let more sediments and water go past the Aswan dam, down the river to the Delta, and allow the renewed muddy floodwaters to spread out into the fields—this has already been done periodically for the Colorado River to rejuvenate the valley sediments in the Grand Canyon.

Although their origin is not completely clear, the ridges may have formed in response to rising and falling sea levels related to global temperature cycles during the Ice Age.[362] We tend to think of this time as a single cold period, but in fact it consisted of many broad cycles of colder and warmer climates, one to two hundred thousand years long, within which there were shorter, more minor climatic variations (Figure 8-13). Each cycle started with rapid warming, as happened most recently thirteen thousand years ago. The climate would then cool slowly as the world entered a new glacial period. Glaciers grew at high latitudes on the continents and to balance this continental storage of water, sea level fell by up to 120 metres. A new cooling cycle should have started but has been interrupted by human-induced climate changes, initially during Palaeolithic times with extensive deforestation and continuing now at a much-accelerated pace with the combustion of fossil fuels.

The story of each ridge started when sea level was at its highest, and the climate was at its warmest (Figure 8-12, Figure 8-13).[360–363] Shellfish grew abundantly in the warm shallow waters, and their shells were broken up by storms. To this debris was added small carbonate spheres called oolites that formed in shallow water. All these loose carbonate sediments were moved eastward parallel to the shore by currents from fair-weather waves to make an offshore bar in shallow water. Winter storms would have made much bigger waves that lifted the sediments and deposited them some distance inland from the shore as a natural berm. When the climate cooled, and the sea level went down, the banks were exposed to onshore winds that winnowed the finer particles and moved them inland, to be deposited on, and in the lee of, the former storm berm. Vegetation grew on the ridge, and the roots drew up groundwater from which calcite crystallized, cementing the sandy grains into limestone.

These limestone ridges are common along the southern and eastern coasts of the Mediterranean Sea.[362] However, there is generally just one ridge, as the process described above was repeated during each glacial cycle, destroying the older ridges. The eight parallel

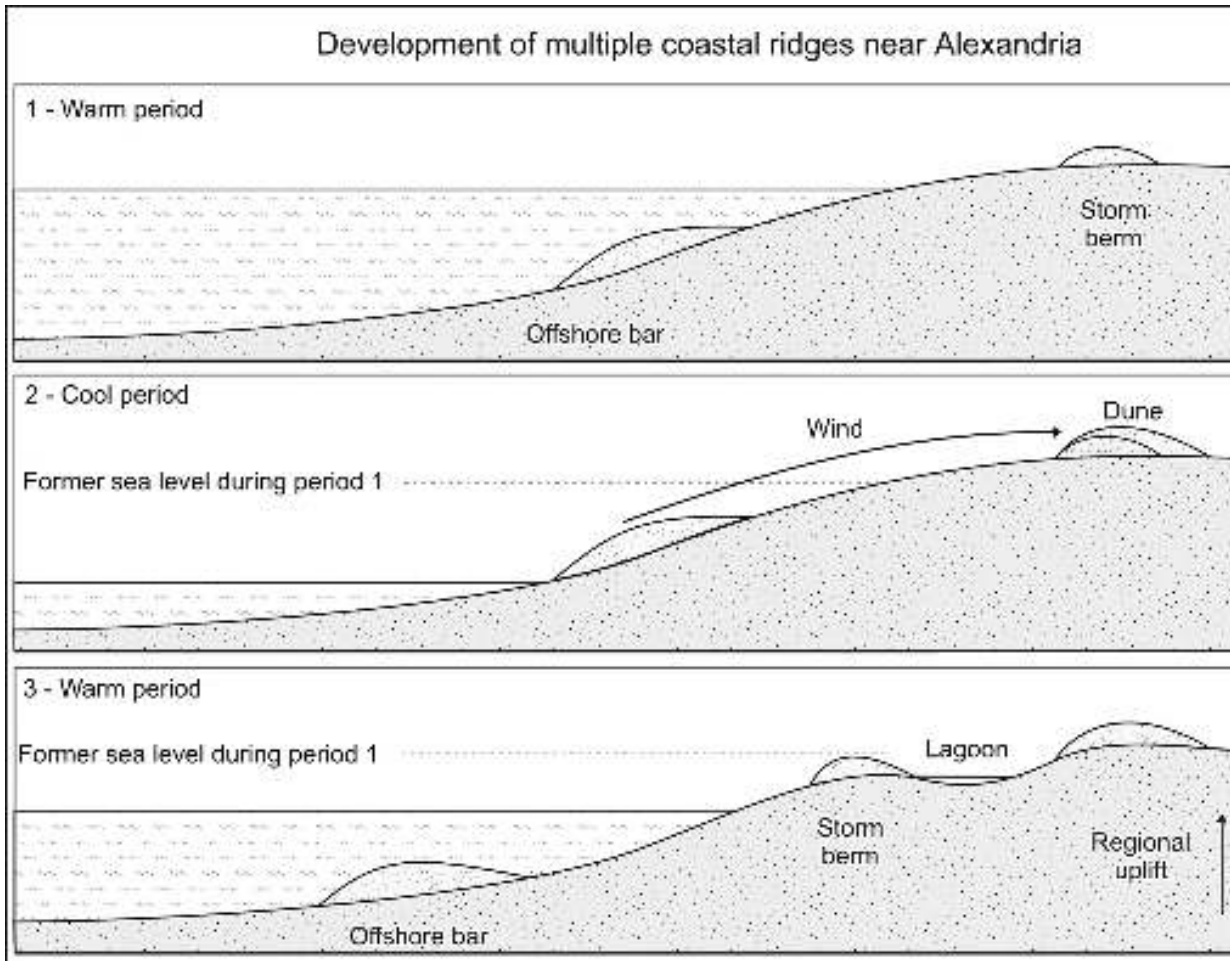


Figure 8-12: Limestone ridges are thought to have developed near the coast during cycles of sea-level changes resulting from global climate changes during the Ice Age and were preserved by regional uplift. Image by the author.

ridges near Alexandria are unusual, although not unique: similar sets of ridges occur on coastal lowlands for 500 kilometres to the west of Alexandria, including at Marsa Matruh where they formed a harbour similar to that at Pharos Island (Figure 8-4).[362] It seems that each ridge was created during a glacial cycle, but was uplifted after its formation, making it more distant from the coast and preserving it from erosion during the next glacial cycle (Figure 8-12). The next cycle then started with the addition of more sediments move in by the eastward current.

In addition to the glacial cycles of sea level changes (Figure 8-13), the land west and south of Alexandria has risen by about 120 metres

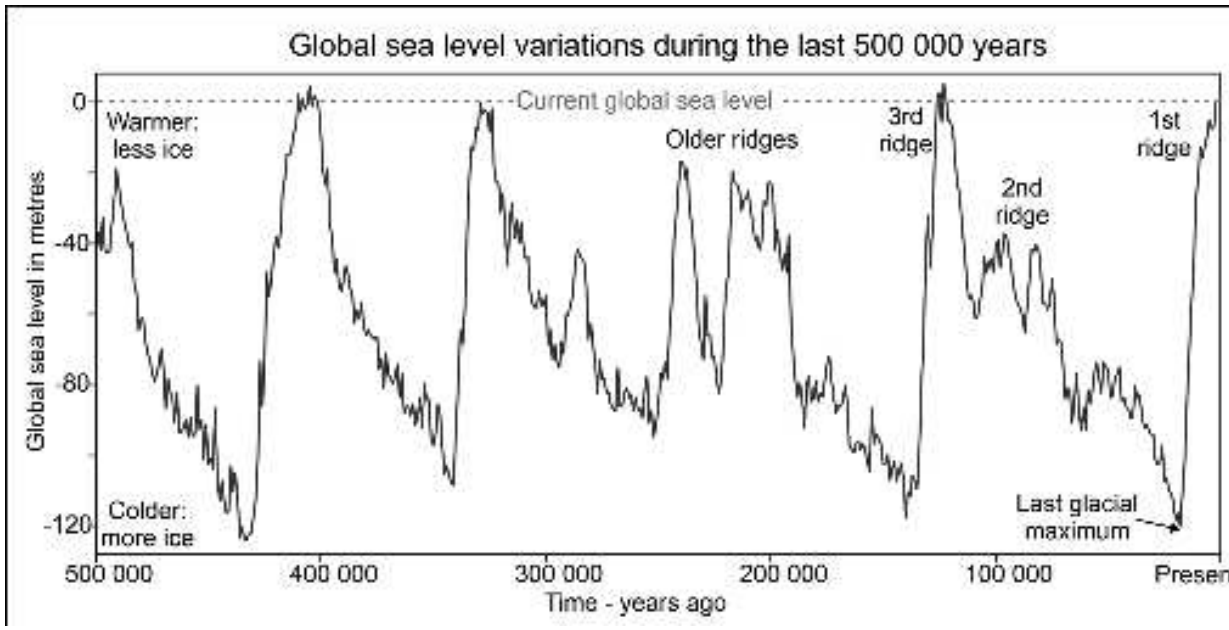


Figure 8-13: During the last few million years, sea level has varied in a sawtooth pattern in response to global climatic cycles. When the climate was cold, glaciers formed, locking up water on land that was balanced by a lowering of sea level. The coastal ridges were formed when the climate was in a warmer phase and sea level was high. The older ridges are not dated well enough that we can associate them with specific peaks in sea level. Image by author after El-Asmar, H.M. and P. Wood, 2000, "Quaternary Shoreline Development: The Northwestern Coast of Egypt." *Quaternary Science Reviews* 19(11): 1137–1149; Lisiecki, L.E. and M.E. Raymo, 2005, "A Pliocene-Pleistocene Stack of 57 Globally Distributed Benthic δ18O Records." *Paleoceanography* 20(1).

during the last million years. Uplift was not constant during this period and the area affected has changed with time, especially close to the Delta. The cause of this uplift is unclear, but it may be a side effect of minor movements along huge cracks in the tectonic plates. One possible culprit runs from Cameroon in West Africa through the Qattara depression and Nile delta towards Cyprus.[364,365] Irregular minor horizontal movements along this crack could have interacted with local faults to produce uplift in the Alexandria region and farther west.

Despite the long history of overall tectonic uplift, paradoxically, the Alexandria region has actually subsided by five metres during the 2,300 years since the construction of the Pharos.[366] Much of this must have happened before 1166 CE when *al-Balawī* mentioned that the causeway and some of the lower rooms of the Pharos were inundated

at times.[346] Some of this subsidence occurred slowly and was a result of upward water loss from the loose, muddy sediments deposited in the Delta (see box 8-3: The Modern Delta). There seems, however, to have been a period of rapid subsidence of 3–4 metres in the 8th–9th centuries that also affected other cities of the northwest Delta (Figure 8-5). It is not clear how this happened or what caused it. The most logical explanation would be an earthquake, but none are known for the region from this period. The subsidence drowned ancient harbour installations and contributed to the collapse of the Pharos, which I'll talk about next.

Decline and Collapse

Like many of the other Wonders, the Pharos was damaged by earthquakes, to which we must add the effects of tsunamis, erosion, and land subsidence, but it was finally destroyed by neglect.[367,368] I will start with earthquakes and tsunamis.

There are relatively few earthquakes in northern Egypt and those tend to be concentrated east of the Delta, along the extension of the Gulf of Suez towards the Mediterranean Sea (see Chapter 2: Pyramids). In most cases, these earthquakes are relatively small and probably only damaged poorly constructed buildings in their immediate vicinity. However, the large but infrequent earthquakes that occur in the Mediterranean Basin from Crete to Syria are a more significant hazard (Plate 16a).

This zone of faults is a broad boundary where the African tectonic plate moves at a speed of 35 millimetres a year towards Europe and Asia. For most of the last six thousand years, the movement has been dissipated either by smooth sliding along the faults or many small earthquakes. However, sometimes the faults become locked and continued plate movement builds up huge stresses in the adjacent rocks. For instance, after seven hundred years the accumulated movement would be 25 metres, which is sufficient to produce a very

Figure 8-14: The effects of land movements during earthquakes are evident at Phalasarna, Crete: the 365 CE earthquake raised the land here by six metres, leaving the harbour dry and preserving an ancient beach and dunes. Photo courtesy of the author.

large earthquake of magnitude 8 or more, as happened in 365 CE and 1303 CE.

At dawn on July 21, 365 CE, a huge earthquake shook most of the eastern Mediterranean region. It was centred in the sea just to the west of Crete, along a major fault where the Mediterranean seafloor dives under the Aegean Sea to the northeast.[369] Movements of the rocks on either side of the fault lifted the land by up to ten metres (Figure 8-14) and also triggered a series of gigantic underwater landslides.[370] However, the most important effect in Egypt was a tsunami (Figure 8-15).

The tsunami affected much of the eastern Mediterranean coast and was particularly destructive in northern Egypt (see box 8-4: Roman

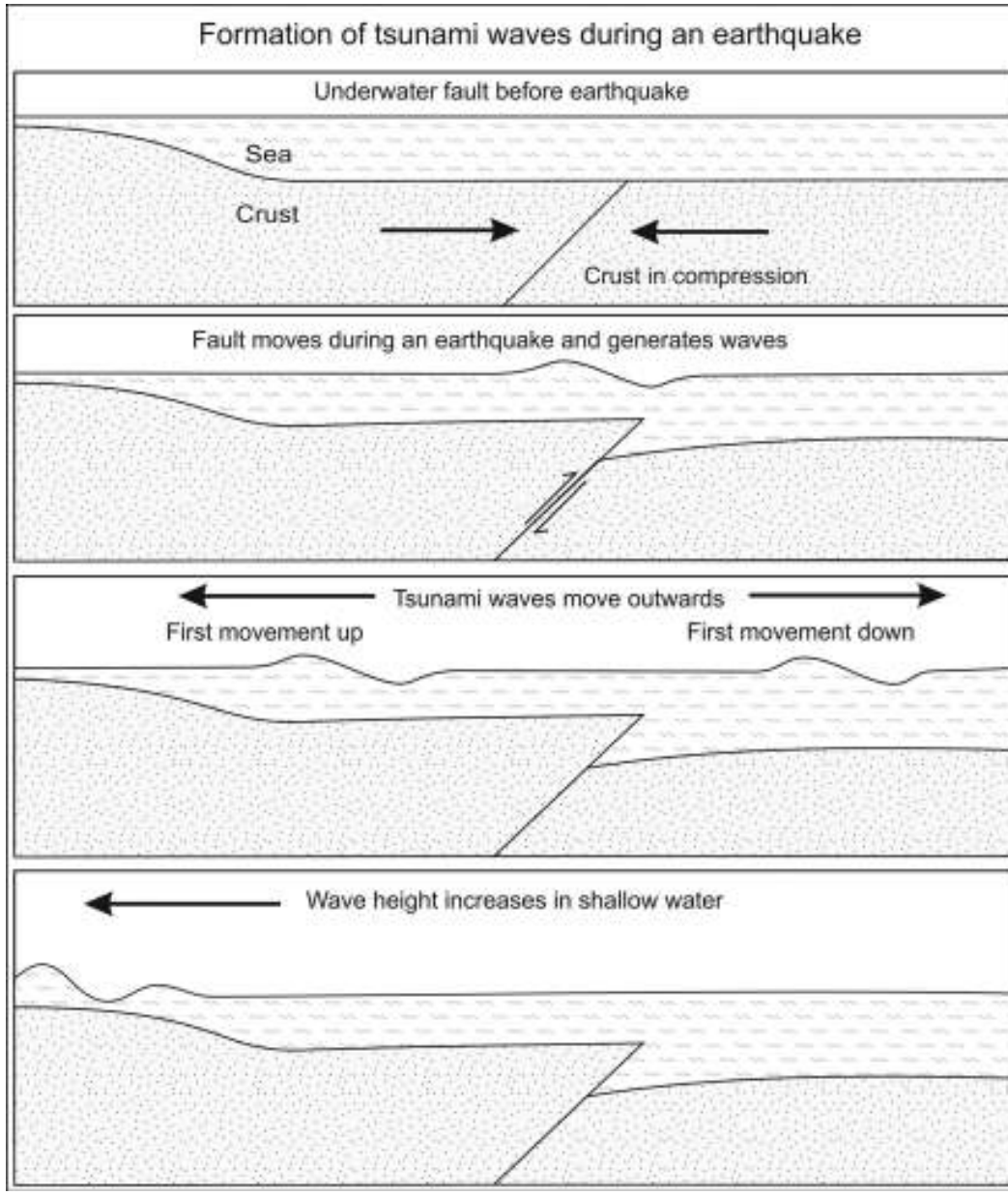

Formation of tsunami waves during an earthquake
Underwater fault before earthquake
Sea
Crust
Crust in compression
Fault moves during an earthquake and generates waves
Tsunami waves move outwards
First movement up
First movement down
Wave height increases in shallow water

Figure 8-15: A tsunami is a series of waves generated by sudden changes in the level of the seafloor during an earthquake, an underwater landslide, or volcanic eruption. In the case of an earthquake, the crust is compressed by tectonic forces on either side of an inclined fault. Stress increases until an earthquake forces the seafloor upwards or downwards. In turn, this makes tsunami waves, which move away from the fault: those that move to the left start with an upward movement, so that when they reach the coast the water moves in rapidly, whereas those that leave to the right start with a downward movement, so that when they reach the coast the water level initially drops. Image by the author.

Box 8-4 Roman Description of a Tsunami

Ammianus Marcellinus gives a vivid description of the 365 CE tsunami and its impact from his observations and other accounts: "Slightly after daybreak, and heralded by a thick succession of fiercely shaken thunderbolts, the solidity of the whole earth was made to shake and shudder, and the sea was driven away, its waves were rolled back, and it disappeared, so that the abyss of the depths was uncovered and many shaped varieties of sea-creatures were seen stuck in the slime; the great wastes of those valleys and mountains, which the very creation had dismissed beneath the vast whirlpools, at that moment, as it was given to be believed, looked up at the sun's rays. Many ships, then, were stranded as if on dry land, and people wandered at will about the paltry remains of the waters to collect fish and the like in their hands; then the roaring sea as if insulted by its repulse rises back in turn, and through the teeming shoals dashed itself violently on islands and extensive tracts of the mainland, and flattened innumerable buildings in towns or wherever they were found. Thus, in the raging conflict of the elements, the face of the earth was changed to reveal wondrous sights. For the mass of waters returning when least expected killed many thousands by drowning, and with the tides whipped up to a height as they rushed back, some ships, after the anger of the watery element had grown old, were seen to have sunk, and the bodies of people killed in shipwrecks lay there, faces up or down. Other huge ships, thrust out by the mad blasts, perched on the roofs of houses, as happened at Alexandria, and others were hurled nearly two miles from the shore, like the Laconian vessel near the town of Methone which I saw when I passed by, yawning apart from long decay." (Res Gestae: 26.10.15–19.)[387]

Description of a Tsunami). In Alexandria fifty thousand homes were destroyed and five thousand people died, and in the Delta, rich farmland was abandoned after flooding and erosion by seawater. The event was so significant that its anniversary was commemorated each year in Alexandria by a festival.[369,371] In the ancient descriptions of the earthquake, the Pharos itself is not mentioned; hence, we may assume that it was not significantly damaged. Fortuitously, this may have been due to the design of the site, with the Pharos set within a walled courtyard. We do not know if this was part of the original plan, but it was clearly described by al-Balawī in 1165 CE. Such a wall could have shielded the Pharos from the tsunami by breaking the wave before it hit the building. Although tsunamis are not that uncommon here, data from drill cores suggest there may have been eight tsunamis or very violent storms in the last two thousand years.[372] It is likely that the wall was constructed to protect the Pharos from erosion by sea spray during winter storms and not from tsunamis.

The Pharos was maintained until 956 CE when another major earthquake destroyed the top 22 metres of the building.[78] Ancient writers reported that it lasted thirty minutes, which is much too long for a single earthquake: strong motions from most earthquakes are generally felt for only ten to sixty seconds. But the thirty minutes could have included aftershocks, which can continue for hours to days after the main shock. There was no significant destruction at Cairo, 160 kilometres to the southeast, so the earthquake must have been close by, perhaps in the Delta. The Pharos must have been repaired after this earthquake, as it was described by al-Balawī in 1165 CE to be in good condition.

On the August 8, 1303 CE, the Pharos was again damaged by a distant earthquake, with an estimated magnitude of 8 or more, which also produced a large tsunami.[78,221,373] Some accounts give the date of this earthquake as 1323 CE, but this was an error in the conversion from Arabic to Western calendars.[78] The earthquake is thought to have occurred near eastern Crete, probably along one of the undersea faults

east of the island, but the greatest damage was in Egypt, particularly in Alexandria: many people were killed when the earthquake brought down parts of the city walls and caused many houses to collapse.[371] The tsunami then inundated the city and completed the destruction. The tsunami also caused major destruction on Rhodes—the former site of the Colossus—and along the eastern coast of the Mediterranean. The earthquake may have also significantly damaged two other Wonders, the Mausoleum at Halicarnassus (Bodrum) and the Pyramids of Giza.

Despite the earthquake and tsunami, the Pharos was still standing in 1326, when the Moroccan traveller Ibn Battúta visited: "I went to see the lighthouse on this occasion and found one of its sides in ruins. It is a very high square building, and its door is set above the level of the earth. Opposite the door, and of the same height, is a building from which there is a plank bridge to the door; if this is removed there is no means of entrance. Inside the door is a place for the lighthouse-keeper, and within the lighthouse there are many chambers. . . . It is situated on a high mound and lies three miles [5 km] from the city on a long tongue of land which juts out into the sea from close by the city wall, so that the lighthouse cannot be reached by land except from the city."[374]

This passage suggests that the Pharos was still in use at that time, as it had a lighthouse-keeper, but that it had been damaged, likely by the 1303 earthquake, and not repaired. It may be significant that Ibn Battúta did not mention the wall around the courtyard that figured in earlier descriptions. Erosion by the sea, now close by, may have destroyed the outer wall, leaving the base of the Pharos directly exposed to sea spray. Salt crystallization close to the surface of the limestone blocks would have caused flaking the rock, weakening the masonry and leaving it more vulnerable to earthquake damage (Figure 8-16).

By this time, trade through Alexandria was severely reduced from its apogee in Roman times: Mediterranean trade had never really recovered from the fall of the Western Roman Empire about nine hundred years earlier and the use of the lake port had declined as the Canopic branch of Nile dwindled in flow. And there was worse to come: European society was upended by the *Great Famine* of

1315–1317 perhaps compounded by an epidemic of typhus. Climatic factors could have triggered both these events, which were amplified by political inflexibility:[375] as in late Ptolemaic times (see box 8-2: Nile Floods and Distant Volcanic Eruptions), distant, but unknown, volcanic eruptions may have caused overall cooling.

In 1347 CE, the troubles at Alexandria grew yet worse with the first arrival of plague (*Black Death*) from central Asia and here too climatic factors may have played a role.[376] The bacterium that causes plague lives in a flea normally carried by gerbils in central Asia. When the failure of the rains triggered a collapse of the rodent population, the number of fleas on surviving animals increased and they were forced to find other hosts, including humans and their domestic animals. The plague moved eastward with traders along the famous *Silk Road* to ports on the Mediterranean Sea, from where it continued along maritime routes to all of the Middle East and Europe. Over the next four years, the disease spread rapidly killing up to half of the population of the region. International trade was all but eliminated, along with the wealth that it created. Further waves of the plague from Asia continued for hundreds of years so that trade was slow to recover.

When Ibn Battúta returned to Alexandria in 1349 CE, he saw the Pharos in total ruin: "On my return to the West I visited the lighthouse again, and found that it had fallen into so ruinous a condition that it was not possible to enter it or climb up to the door." Following the collapse of the Pharos, the sultan ordered construction of a small watchtower, but it was never finished and this Wonder of the World was never rebuilt.

Blocks from the walls of the Pharos lie on the seafloor, scattered up to 80 metres away from the base, which means that the collapse must have been catastrophic and spectacular (Figure 8-7). It must have happened between the two visits of Ibn Battúta in 1326 and 1349 CE, but since there were no significant earthquakes recorded for this period, the collapse was probably caused by the failure of the foundations. The Pharos was built on a layer of coquina limestone, which was underlain by loose, uncemented sand (Figure 8-16). At the time of the construction, the platform was about ten metres above sea level: winter storms

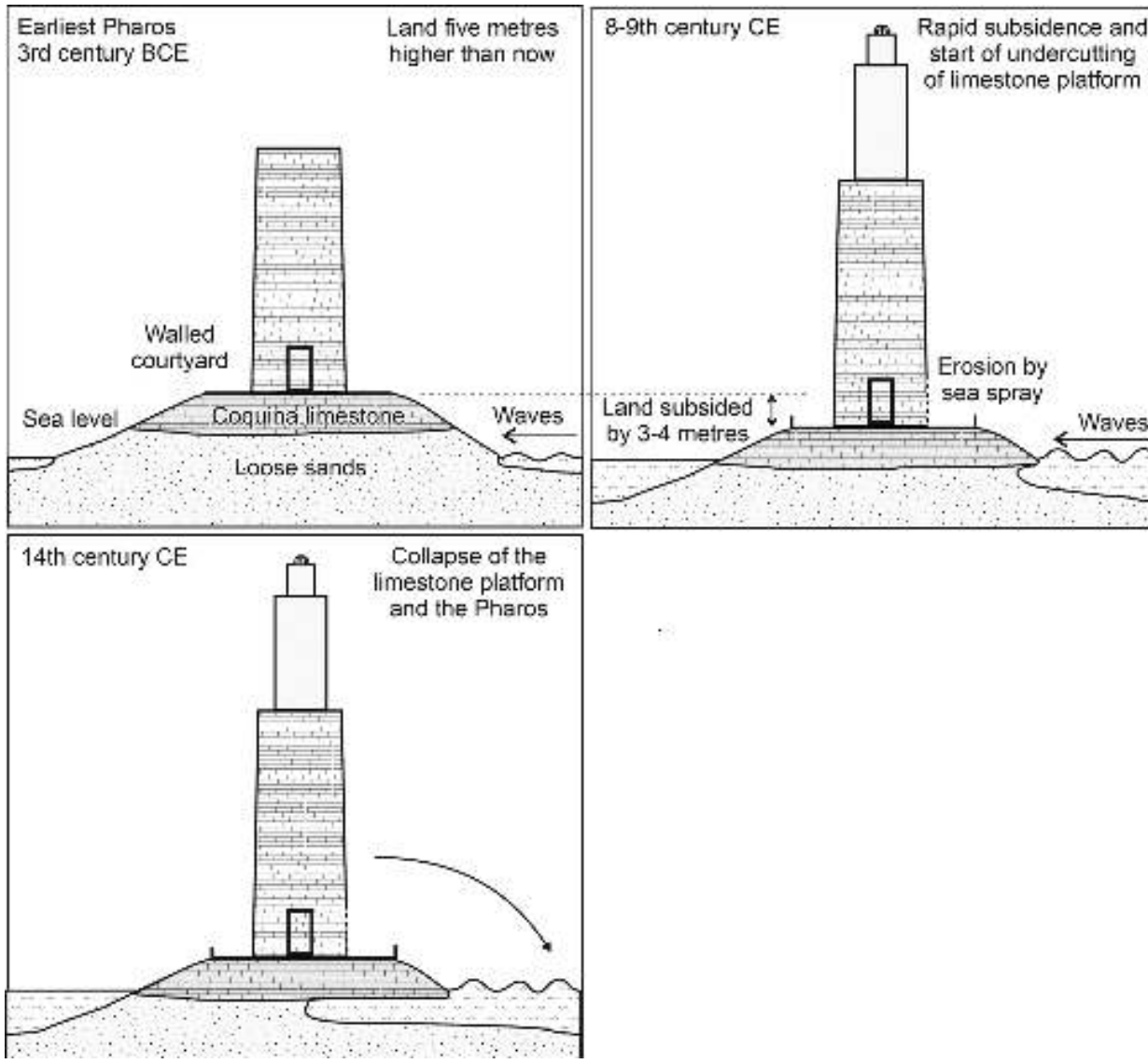


Figure 8-16: When the Pharos was originally built, the sea was far from the base of the building. Subsidence of the land caused the sea to encroach: erosion then damaged the walls and waves undercut the limestone platform until it collapsed, bringing down the Pharos. Image by the author.

and occasional tsunamis would have eroded the underlying sands, but the coastline was far from the Pharos so it was secure. Since then the land has sunk five metres, effectively raising sea level and leading to erosion of the sands from under the limestone platform itself.[366] Most of this subsidence occurred in the 8th–9th centuries. By the 12th century, waves had undercut the western side of the platform and the hole was filled with old columns.[377] However, erosion continued on

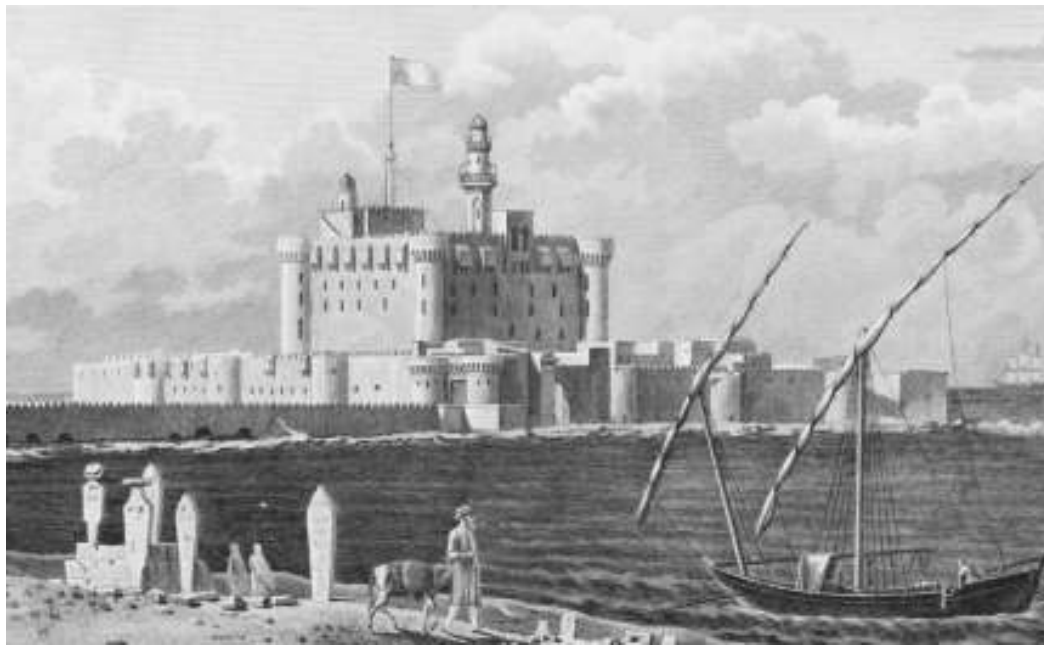


Figure 8-17: Qaitbay Fort was built close to the site of the Pharos in 1479 CE. To give an idea of scale, I should mention that the Pharos was about five times higher, on a similar-sized base. This image was drawn by Napoleon's scientific team and shows how the fort appeared after repairs in 1798. Panckoucke, C.L.F. and É. Geoffroy-Saint-Hilaire, 1809, *Description de l'Égypte ou Recueil des observations et des recherches qui ont été faites en Égypte pendant l'expédition de l'armée française*. Paris.

the eastern side, eventually causing the platform to collapse, bringing down the entire structure.[340,347]

The ruins of the Pharos were left largely undisturbed for over a hundred years until 1479 CE when Sultan Qaitbay built a fort to defend Alexandria from the Ottoman Empire (Figure 8-17).[378] Qaitbay Fort was constructed close to the site of the Pharos, using some stone from the ruins, but not the ancient foundations, which were largely destroyed during the collapse and were partly underwater.[347] There was a major restoration of the fort in 1939, which included a breakwater that partly covered the underwater remains of the Pharos. In the 1990s, another breakwater of huge concrete blocks was built right across the presumed site of the Pharos. This provoked an outcry that resulted in an underwater archaeological survey and excavations. The ruins are now an unusual tourist attraction for visitors and divers.[379]

9

Rebuilding the Wonders

Introduction

In the previous chapters, I discussed the construction and demise of the Seven Ancient Wonders but here I want to speculate about how we could create modern replicas using modern science, engineering, and technology. Of course, this is not necessary for the Pyramids as they still exist but I have included them in the exercise for completeness. I will try to mitigate some of the ethical and environmental issues concerning such projects by building my New Wonders beside the remains of the Ancient Wonders, rather than on top. Once completed, the reconstructions would undoubtedly have educational value, helping to illustrate the majesty of Ancient Wonders and become destinations for tourists interested in the past.

The Ancient Wonders lasted from 60 to 4,500 years, which is a huge contrast with the typical design life of fifty years for most modern buildings, although there are rare exceptions to this short-sighted view. We have to go to other fields to see true technological longevity: the *Clock of the Long Now*, for example, designed to operate for ten thousand years.[388] For the sake of this exercise, I've chosen a more modest goal and decided that my New Wonders should last for two thousand years with only minor maintenance. It is this concept of longevity that distinguishes my projects from similar plans that fill the Internet.

My New Wonders are designed to resist those natural processes that most affected the Ancient Wonders, such as weathering, erosion, earthquakes, and tsunamis. I assume that the high levels of air pollution encountered in many modern cities are only a temporary problem, otherwise there will be no significant human population to appreciate the structures. A longer-term problem is human-induced climate change. Higher air temperatures may make human life difficult in some parts of the world—Iraq, for instance—but should not directly affect most of the New Wonders. However, the projects must be designed to accommodate rising sea levels, which are difficult to predict on the time scale of this project. If all the glaciers melted, then the sea would rise by 70 metres, drowning the sites of all the Wonders except Nineveh and perhaps creating a set of *New Wonders of the Underwater World*, but here I will take a more optimistic prediction of less than five metres, which will only affect the design of one or two of my New Wonders.

The most important imponderable is the deliberate destruction of my New Wonders in response to religious or political movements: this was the fate of many ancient monuments including at least two of the Ancient Wonders. It does not seem likely to me that the future will be any more secular, apolitical, and logical than the past, much as I would like it to be, so I have designed my New Wonders to withstand as much as possible both human and natural forces. Let's now see how the Ancient Wonders could be recreated.

A New Pyramid at Giza

The Pyramids are still standing but for the purposes of this exercise, I will assume that we want to build the New Pyramid on the Giza Plateau to the northwest of the existing structures.

The Wondrous Pyramids have stood on the Giza plateau for 4,500 years and have never developed any significant structural cracks, which means that the underlying bedrock was strong enough to support the

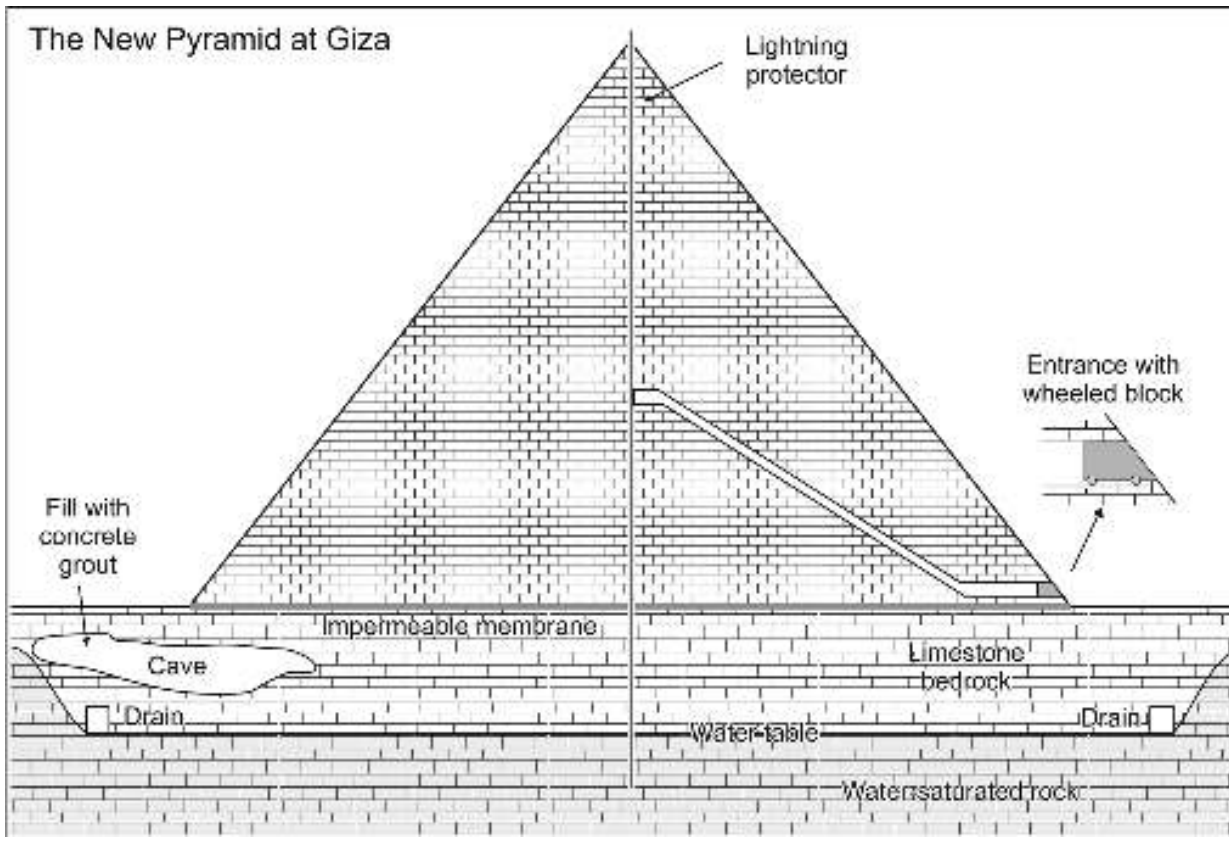


Figure 9-1: A section through the New Pyramid. Image by the author.

gigantic weight of these structures without subsidence. Recently, the subsurface environment has changed with the construction of vast suburbs all around the Giza plateau: water leakage from supply lines and sewers has raised the water table so that it is now close to the surface.[45] This has produced several problems: groundwater is drawn up into the pyramids and other ancient structures by capillary action, where it evaporates making salt crystals that can flake off the rock surface. In addition, variations in the level of the water table can enlarge fissures and caves in the limestone bedrock, weakening the foundations.

With this in mind, we will need to do a geophysical survey to locate the water table and voids, build a drain around the site's periphery to prevent further damage, and fill in cavities by injecting concrete through holes drilled in the bedrock ("grouting") (Figure 9-1). As a final measure, I would suggest installing an impermeable barrier

made of stainless steel between the bedrock and the new building to prevent groundwater rising into the new structure by capillary action.

The core of the ancient pyramids was built from stone quarried from the Giza plateau, but aesthetic considerations mean that we must locate another source for the New Pyramid, which should not be difficult as this same stone is quite widespread. The ancient workers used copper chisels to extract the stone but we will be using large diamond-impregnated circular saws, which are much faster and have the additional advantage of producing precisely cut blocks. The higher-quality limestone used for the casing was obtained from quarries to the east of Cairo and I would suggest using the same source. Again, we will be precisely cutting the blocks, including their inclined outer surface, using circular saws. The ancient pyramids contained significant amounts of granite from Aswan and, yet again, we could use the ancient source. For granite, the contrast between modern and ancient cutting techniques is much more extreme: ancient workers had to remove granite by laboriously pounding the surface in wide trenches whereas we can cut a thin slot thousands of times faster with our diamond-impregnated saws. We do not have to laboriously move stone blocks by land or water and raise them with ramps and levers, as was done in antiquity, but instead, we can simply transport them by truck and use cranes to lift them into place on the pyramid.

The core of the original pyramids was made of irregularly shaped blocks and the spaces were filled with gypsum mortar. For the New Pyramid, I'm suggesting that the blocks are rectangular and cut to a standard size so that they can be securely set without mortar. This will save time and materials and is also an anti-seismic measure, as in the unlikely event of a major earthquake the blocks will just rub against each other and dissipate the energy of the seismic waves. However, more seismic protection is needed on the outer faces of the pyramid where the blocks are not constrained on all sides. In the original pyramids, the facing blocks were loosened during the great earthquake of 1303 CE giving looters access to the rest of the

casing. For the New Pyramid, we will try to avoid this problem by linking the casing blocks to the core using titanium U-clamps set in lime mortar, which is chemically and physically compatible with limestone.

Once the Pharaoh had been buried, the interior galleries of the original pyramids were sealed off, but I don't want to do this as it will invite damage to the structure by the curious, even if there is not going to be anything of value inside. In the New Pyramid, the internal galleries could be closed with a door made of stone blocks that can be pushed into the pyramid on metal rails when access is needed for technical or touristic reasons.

Lightning has struck the ancient pyramids many times, breaking the uppermost blocks and removing the uppermost few metres. For this reason, I would suggest protecting the New Pyramid by installing a copper spike at the top, linked to the underlying water table by a copper wire integrated into the stonework during construction.

New Gardens in Iraq

Although the Wondrous Gardens have been traditionally situated at Babylon, there is a growing opinion that they were at Nineveh, which is where I will put my New Gardens, for reasons that I will elaborate below.

Iraq is already a very hot place in the summer and human-induced climate change will only make this worse: we may hope that the global climate returns within a hundred years to a state more typical of that when the ancient gardens were built 2,500 years ago, but we must still design the New Gardens with extreme heat in mind.

I visualize the New Gardens on a series of terraces set into the side of an artificial hill built on vacant land northeast of the ancient palace and purported garden at Nineveh (Figure 9-2). The whole structure will rest on foundations of reinforced concrete slabs onto which we will lay locally quarried limestone blocks. In keeping with ancient

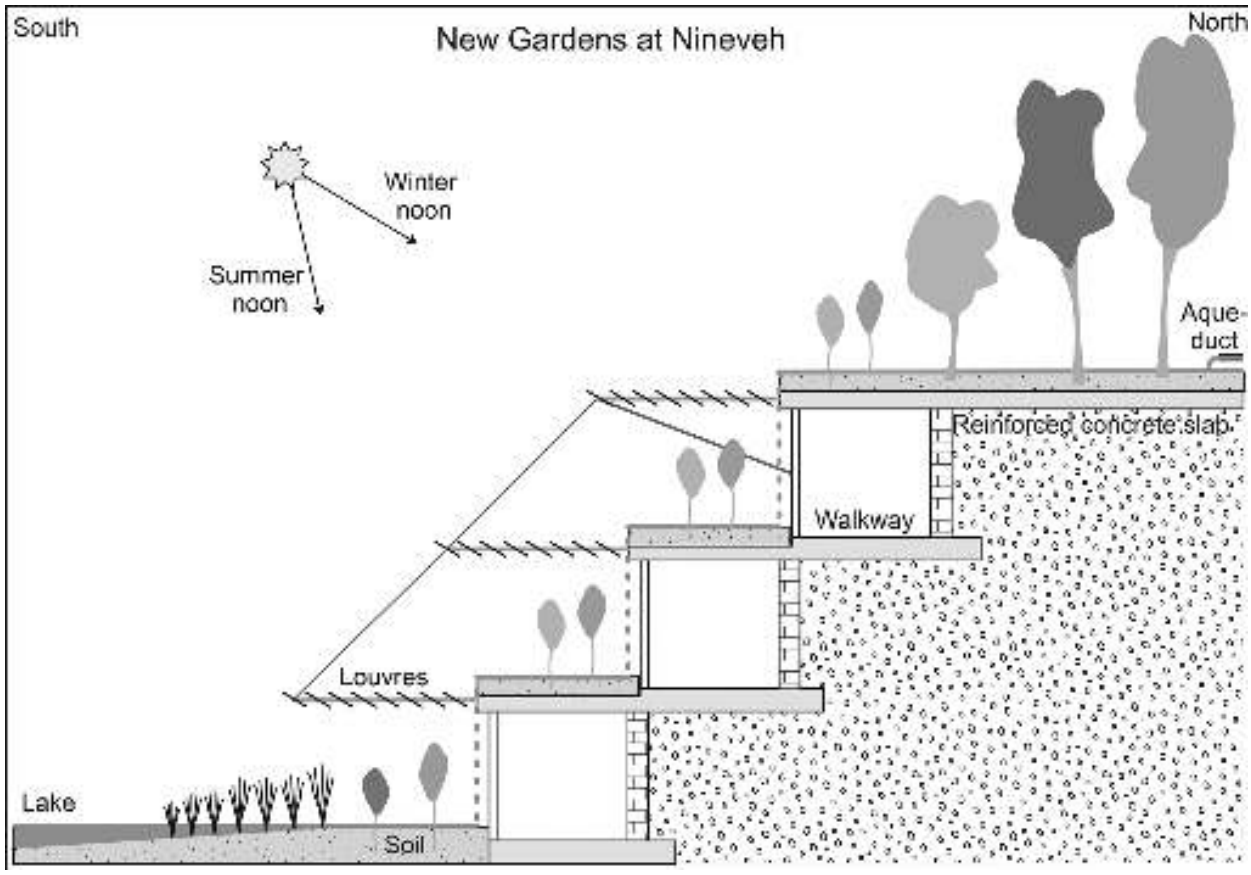


Figure 9-2: The New Gardens will be built on the southern slopes of an artificial hill in Nineveh. Image by the author.

technology, we too will use bitumen to waterproof the terraces. Soil will cover the bitumen, protecting it from direct heat and light, so it should last for hundreds of years before it has to be renewed. Underneath these terraces, cool shady corridors will be a pleasant place to stroll and admire the gardens.

The design of the New Wonder must consider increases in summer temperatures since antiquity. To this end, I am suggesting that the terraces be covered with corrosion-resistant metal louvres that reflect the summer sun but allow its rays to reach the plants in winter (Figure 9-2). The cooling effect of the louvres could be enhanced by painting them with the recently developed barium sulphate white paints, which not only reflects the entire range of solar radiation, from ultraviolet through visible light to the near infrared, but also dissipates heat directly into space at far-infrared wavelengths, where the

atmosphere is transparent.[389] This same coating could also be applied to other solid surfaces exposed to the sun.

In a dry climate, gardens need water and, as in antiquity, an irrigation system will certainly be an essential part of the project. The new aqueduct will closely resemble the ancient system and take water from perennial springs issuing from limestone in the mountains to the northeast. This water is saturated with calcium carbonate that must be reduced, otherwise it will precipitate on the walls of the aqueduct, eventually blocking the system and necessitating significant maintenance during the design life of my project. The easiest way to diminish this problem is to let the stream go over waterfalls, which releases carbon dioxide allowing calcite to precipitate out before the water enters the aqueduct. However, even with these measures, maintenance will probably be necessary every century or so. In the final part of my aqueduct, water will be conveyed under pressure in a stainless-steel tube to the highest terrace. From there it will flow in channels along the terraces, cascading down to further cool the corridors and finishing in an artificial lake.

High temperatures are not only a problem for humans and other animals but also for plants: the enzymes that enable photosynthesis are much less efficient at temperatures over 40°C. However, some tropical plants, like maize and sugarcane, have a slightly different photosynthetic mechanism that reduces this problem. At the moment there are very few trees that use this photosynthetic route, but perhaps this could be changed by genetic engineering. Certainly, such heat-tolerant trees would be ideal for the New Gardens as they could provide shade for more conventional plants.

The garden's organic components will, of course, need constant maintenance. Although some trees do survive for up to two thousand years, the oldest specimens live at high altitudes where growth is restricted to a few months a year. My plan is to plant trees and bushes with shorter lives that will be replaced regularly. Of course, I expect periods of neglect with plants dying of thirst, but the structure of the New Gardens will survive to be planted anew when stability returns.

A New Temple and Statue at Olympia

The ancient statue of Zeus at Olympia was enclosed within a temple and one cannot be rebuilt without the other. I suggest building the New Temple and Statue near the modern entrance to the sanctuary. This does not have quite the same setting as the original but avoids widespread ancient remains in the main part of the site.

The new site would be no less susceptible than the first temple of Zeus to inundation by mud and debris brought down by the Kladeos Stream. In antiquity, the site was protected by a wall, but it was not a long-term success as it was breached many times. In the new project, I would have flood protection moved up the Kladeos valley, away from the sanctuary, with the construction of sediment retention dams. The basins behind the dams will eventually fill up with sand and mud, but maintenance is easier higher up in the valley than at the new site after it has been flooded.

Like the original location, the new site would be vulnerable to landslides and soil shed from Mount Kronos. In antiquity, this problem was moderated by a retaining wall at the base of the hill and this is the solution I propose for the new site, with the addition of drainage pipes in the hill. Water discharged from the pipes could be used to feed fountains near the temple. The foundations of the New Temple will also need to be drained by pipes discharging into the adjacent valley.

Olympia is in a zone of high seismic risk, and potential earthquake damage is increased by the loose sediments that underlie the site, which can resonate, amplifying surface vibrations. Strong bedrock is out of reach deep beneath the site, so to reduce the risk of damage by earthquakes, I envisage building the New Temple on a rigid base supported by piles, as I have proposed for the New Pharos (Figure 9-6). Such a base would be made of concrete, reinforced with stainless-steel bars.

I have designed the New Temple to withstand seismic vibrations that can be transmitted up through the base. Instead of the structurally weak local limestone that was used for the original temple, we will

build the New Temple with stronger limestone or marble imported from the eastern Peloponnese. The wall blocks will be linked with mortise and tenon joints and tied together with titanium U-clamps. The columns are the weakest part of the temple so I have designed them to rock slightly during an earthquake while remaining rigid (Figure 9-3). I suggest that the roof beams are made of aluminium,

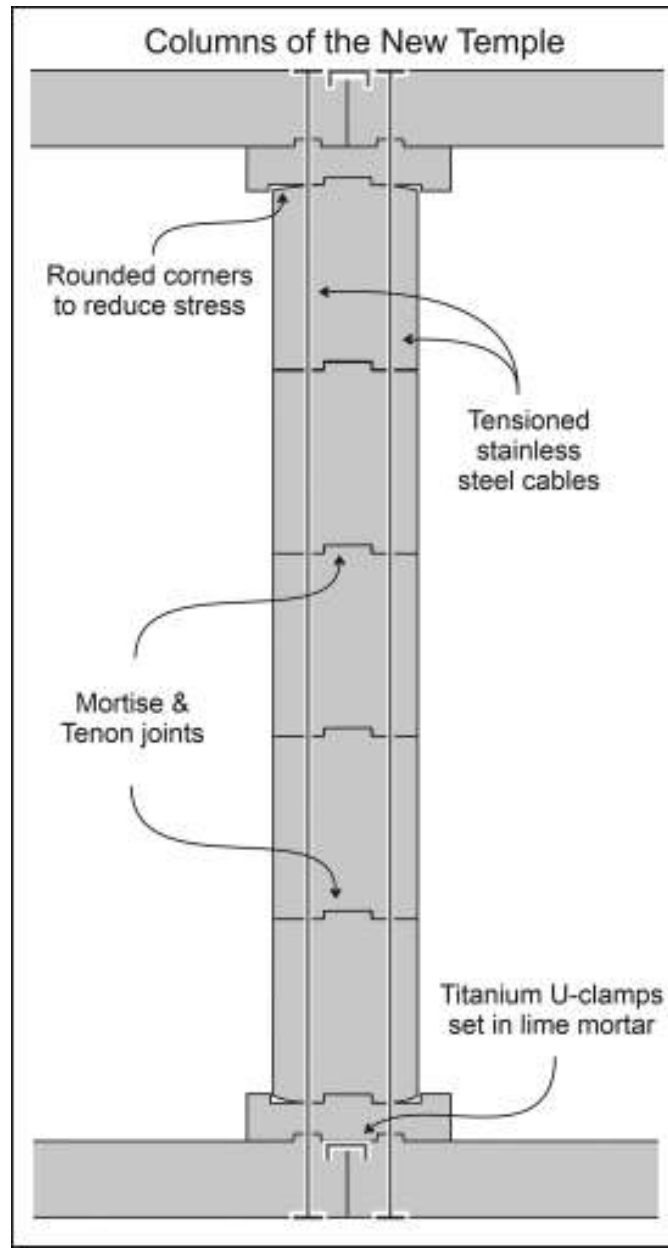

Columns of the New Temple
Rounded corners to reduce stress
Tensioned stainless steel cables
Mortise & Tenon joints
Titanium U-clamps set in lime mortar

Figure 9-3: Anti-seismic measures will be used for the columns of the new temple. During an earthquake, the column will remain rigid and pivot at the top and base. Image by the author.

instead of wood, for longevity and reduced maintenance. The whole structure will be covered with marble tiles interspersed with non-traditional glass tiles to illuminate the statue.

The wondrous statue had a wooden frame but for my statue, I am suggesting a stronger and more dimensionally stable core made of welded aluminium. The original drapery of the great god was cast from pure gold but we could try making panels using a 3D printer with cheaper and stronger gold alloys. To prevent galvanic corrosion, I suggest fixing the panels to the framework with glass-fibre insulators. We cannot use ivory for the skin but we can replicate its appearance using porcelain ceramic panels, which are also much more durable. We will design both gold and ceramic panels so that they do not crack or bend when the statue's framework is slightly twisted during earthquakes. As for the throne, the same methods will be applied: the metal framework will be completely covered with sculptured gold, porcelain, and wooden panels.

A New Mausoleum at Bodrum

The New Mausoleum, to be built just north of the original, will face the same geotechnical problems as the ancient one: a high-water table, weak bedrock, and high seismicity. These problems were also encountered at Olympia and here I take a similar approach to dealing with them.

The new site will need excavating down to more consolidated rock and filling with a slab of reinforced concrete. We know the overall form of the ancient building so it will be relatively easy to construct a new one using the same materials, quarried at the same locations: blocks of volcanic rock from the western part of the Bodrum peninsular for the solid core of the building and white marble from northwestern Turkey for the outer facing. All blocks will have mortise and tenon joints to tie them to the underlying blocks, as well as titanium U-clamps set in lime mortar to link adjacent

blocks. I suggest that the columns in the upper part of the building are protected from damage by earthquakes in a similar way to those at Olympia (Figure 9-3).

I see the New Mausoleum, like the ancient one, richly decorated with marble statuary and panels, carved using modern power tools. As free-standing statuary is particularly sensitive to damage by earthquakes, they will be tied to the body of the building with stainless-steel rods and cables designed to allow for a certain amount of movement.

The ancient Mausoleum stood in a huge courtyard within marble walls, which we can easily replicate. I imagine a vast space filled with trees, watered from a spring that issues at the base of Göktepe Hill. This will be a minimal-upkeep garden designed to provide shade and make a visit to the New Mausoleum more comfortable.

A New Temple at Ephesus

The Wondrous Temple of Artemis was built on the shores of a gulf, which has since disappeared having been filled in by sediments deposited from the Küçük Menderes River, so to be as authentic as possible we must recreate the ancient landscape as well as the temple (Figure 9-4). I envisage building the New Temple just south of the original and having it face onto an artificial lake, that will be fed by the river and retained by a low barrage to the west made from the excavated sediments. The new lake level will have to be at least 5 metres higher than that of the original gulf to accommodate rising sea levels. In my plan, visitors will be able to access the site by small boat through a canal and lock that runs from the sea to the lake.

The Küçük Menderes River is quite muddy and to prolong the life of the lake, these sediments must be removed. I suggest doing this by impounding the river upstream from the lake behind low sediment retention dams constructed from one side of the valley to the other. A floodway from behind the last dam will take excess water from winter storms directly to the sea. Of course, this system of flood control will

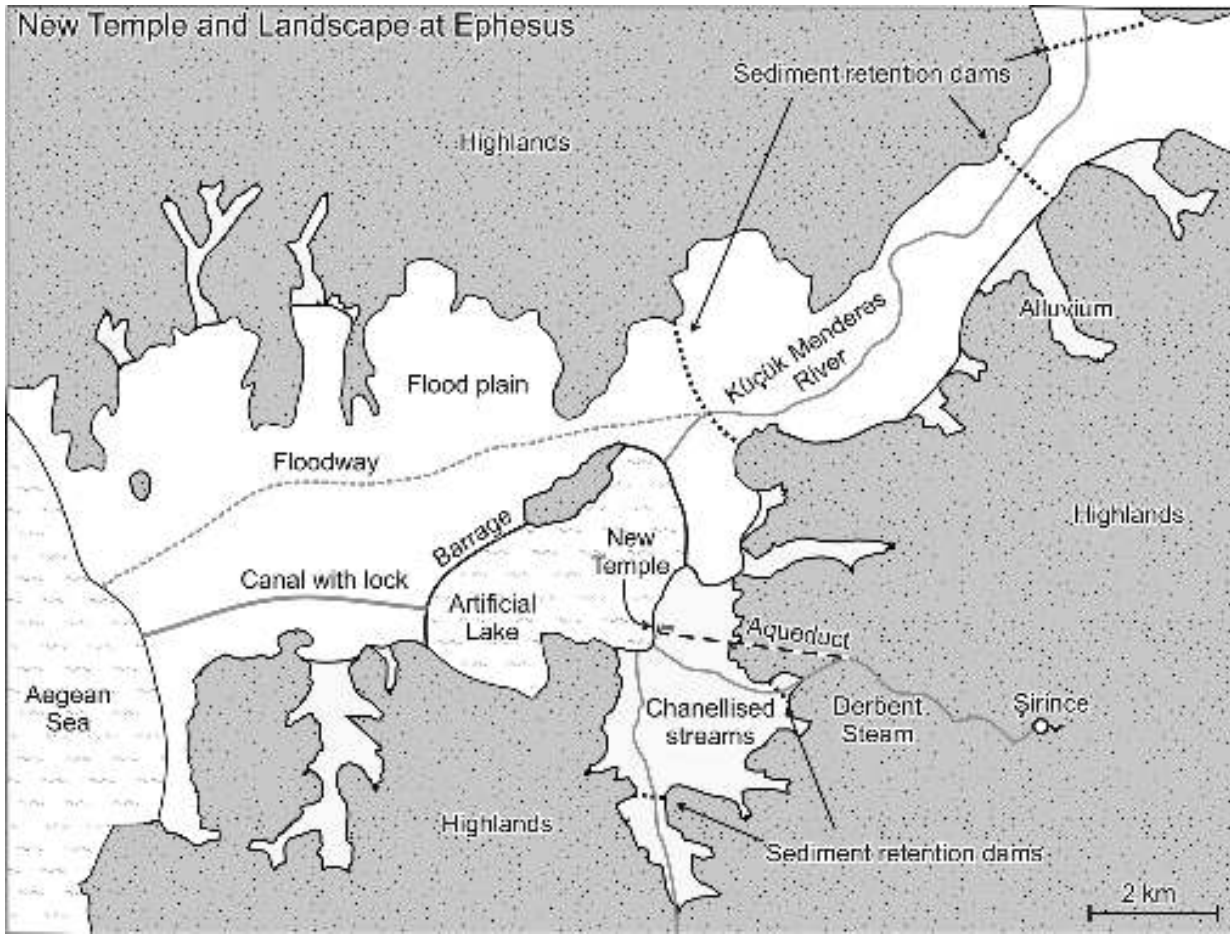


Figure 9-4: The New Temple will be sited in an artificial landscape resembling that which existed around the original Wonder. Map by the author.

need regular maintenance to clear out accumulated sediments and repair the dams.

Like the site of the Ancient Wonder, the New Temple is threatened by flooding from streams flowing from the east and south. We can reduce the risk by using the same strategy as for the river, as well as a few others: deepening the stream channels and building a wall around the site.

I've talked about how the builders of the Wondrous Temple were aware of the high frequency of earthquakes in this area and used some anti-seismic construction techniques, but we do not know how effective they were. Today, there is an additional problem: the water table is closer to the surface and such water-saturated sediments will behave

like a liquid during an earthquake with disastrous consequences for the New Wonder. This means that the site of the New Temple will have to be excavated down to bedrock where possible and where not, deep stainless-steel piles will be needed (Figure 9-6). For the foundation slabs for the Artemis Temple and Altar Court, I am suggesting reinforced concrete slabs, as I have for many of the New Wonders.

For the platform, walls, and columns of the New Temple, we can use marble extracted from quarries close to those used for the ancient temple. The anti-seismic measures will be similar to those proposed for New Temple of Zeus and the New Mausoleum (Figure 9-3).

A vital part of the original sanctuary was a natural spring that does not exist anymore. We will replace it with a basin fed by a stainless-steel pipe that will take water from the lower part of the Derbent Stream. Since most of the calcium carbonate from the spring at Şirince is precipitated out in waterfalls well upstream from our aqueduct, calcification of the system is unlikely to pose a problem.

A New Statue at Rhodes

Recently, there have been proposals for the construction of a statue 150 metres high astride the harbour. We know that a statue this type and size could not have been made in antiquity and my New Colossus will resemble more closely the original wonder, an upright figure holding a torch above his head.

I propose to build the new statue near the southwest corner of the ancient harbour where it would be visible from the water and partly protected from tsunamis and sea spray by the quays. This site is close to the Palace of the Knights, one possible location of the original Colossus.

An earthquake toppled the Colossus only sixty years after its construction, and the region is still seismically active, so I have designed the New Statue to withstand the strong forces that occur during earthquakes (Figure 9-5). The foundations are not a problem here as the

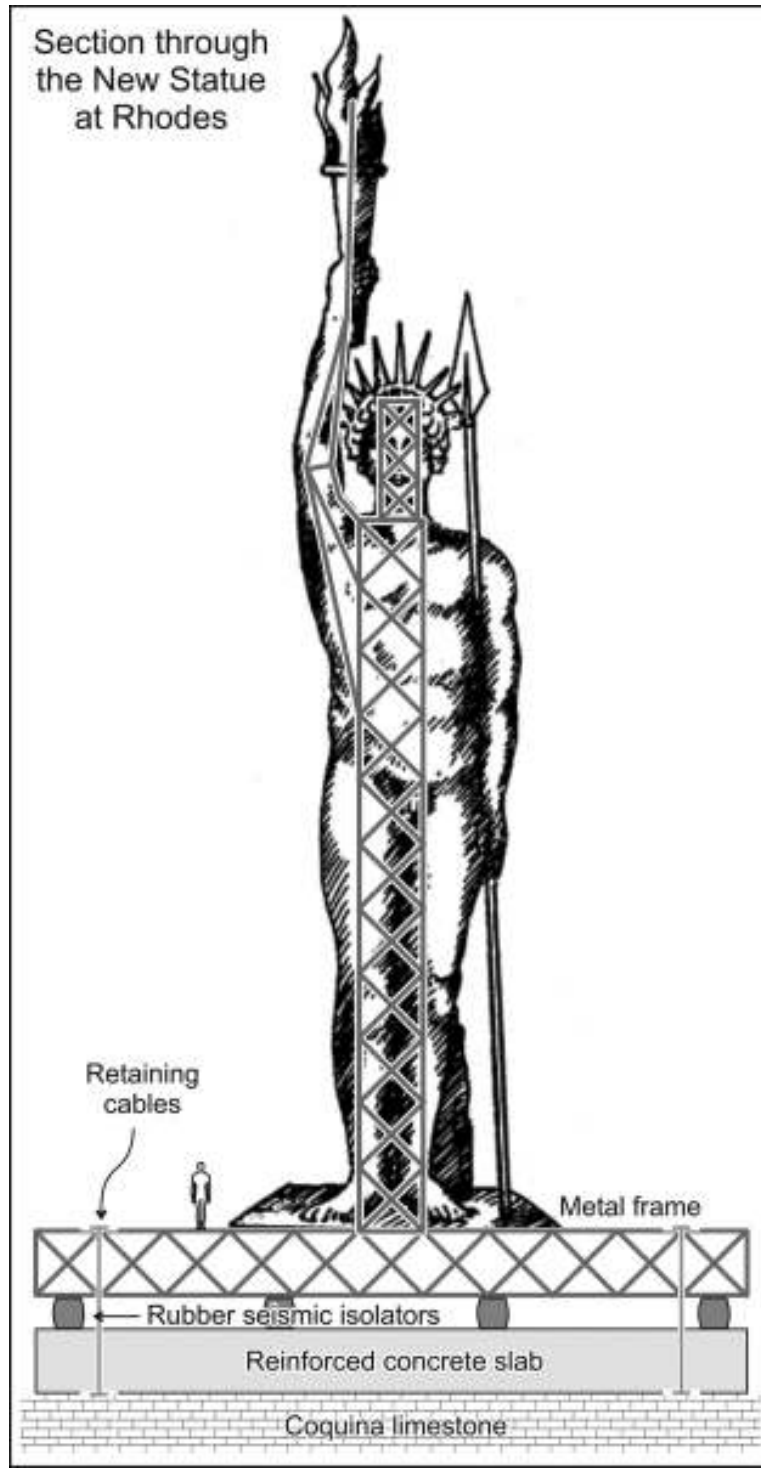


Figure 9-5: The New Statue will be built on a cross-braced metal framework linked to a wide base and seismically isolated by rubber blocks set on a concrete base that rests on bedrock. The rubber isolators will be replaced every hundred years. Image by the author.

coquina limestone bedrock is close to the surface and can support the statue's relatively modest weight of 150 tons. Since the New Colossus will resemble the original wonder, a high, narrow structure that is particularly sensitive to seismic vibrations, I suggest building it on a rigid base and framework of stainless-steel girders seismically isolated from the foundation slab by rubber blocks. The whole structure is designed to be somewhat flexible so that the statue can sway without breaking during an earthquake. We will cast large bronze plates and fix them to the framework with flexible insulating insulators, to prevent galvanic corrosion and allow a certain freedom of movement. I plan to make the interior of the statue accessible for maintenance and tourism, a bit like the Statue of Liberty in New York.

A New Pharos at Alexandria

I envisage that the New Pharos will cover the top of a low hill a few hundred metres to the west of the original structure, now underwater, and a mediaeval fort.

The original Pharos collapsed after its foundations were undermined by the sea and I've designed the New Pharos to ensure that it does not happen again. Since the likelihood of this problem is partly determined by the proximity of the sea, my plan calls for foundations rising 10 metres above current sea level, so that the building will be protected, even after 5 metres of sea level rise. As in the original Pharos, a walled courtyard will reduce the impact of storm waves and tsunamis, supplemented by rip-rap, a pile of large, irregular stone blocks that dissipate wave energy (Figure 9-6).

Although earthquakes are not common here, we know that the upper parts of the original Pharos were damaged on several occasions and the New Pharos is designed with that in mind. As I have suggested for other wonders, the foundations comprise a slab of reinforced concrete with stainless-steel piles driven deep into the underlying materials (Figure 9-6). As in the original design, the New Pharos will be

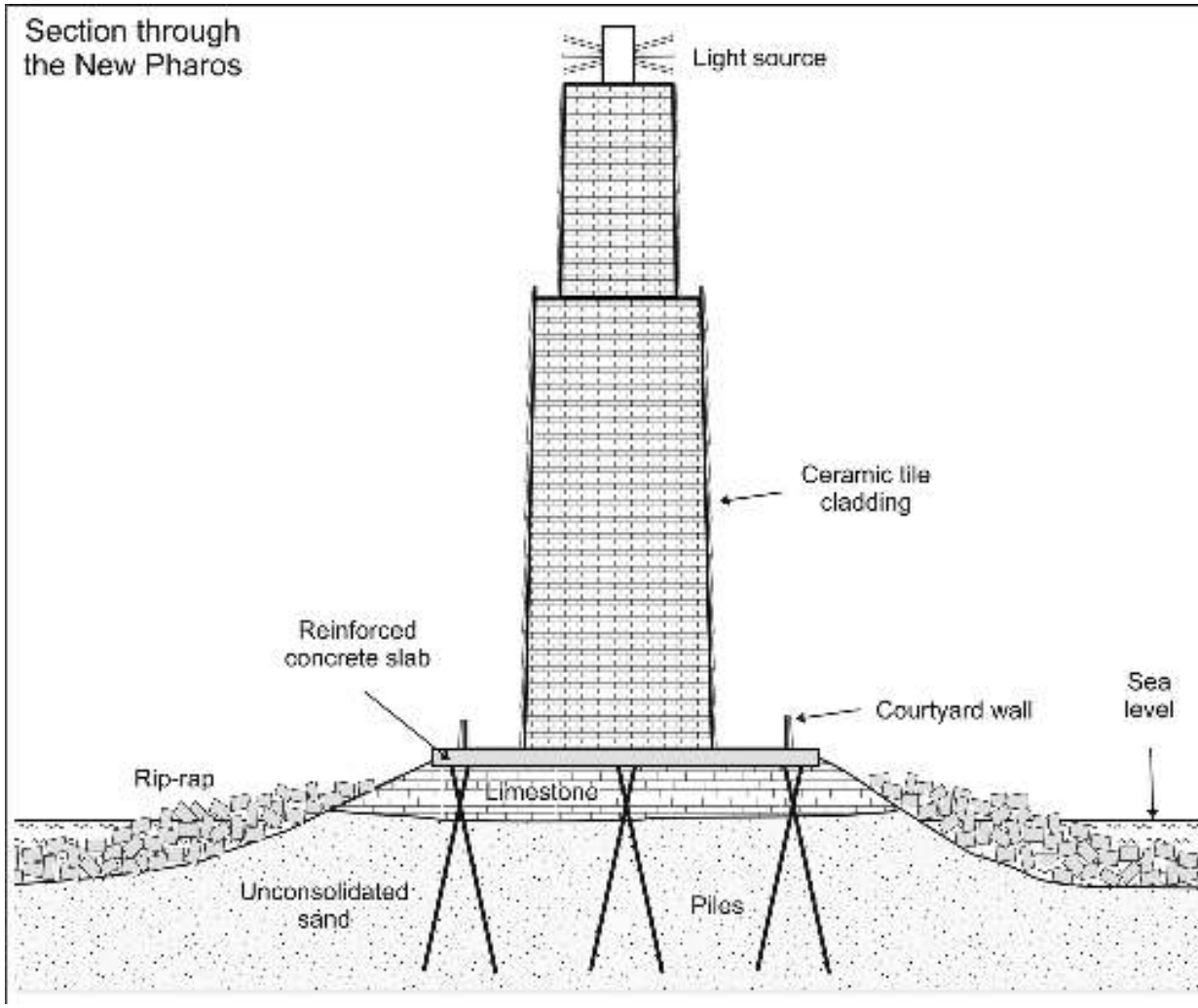


Figure 9-6: The New Pharos will be built on strong foundations to protect it from undermining by storms and tsunamis. Image by the author.

built of blocks of local coquina limestone, with decorative elements in granite. To reduce damage caused by earthquake vibrations, blocks will be linked vertically by mortise and tenon joints, and horizontally by metal U-clamps. The local limestone is very susceptible to weathering caused by the absorption of sea spray, so I propose that all exposed surfaces are covered by large, overlapping ceramic tiles, coloured to resemble stone and fixed with corrosion-resistant metal pins. The balconies and roof will be decorated with bronze statues, carefully tied to the structure with stainless-steel rods and cables. Like the original Pharos, it will be possible to go inside for maintenance and tourism.

Although the original Pharos did not have a permanent light until one was installed during Roman times, most people will expect the New Pharos to be a lighthouse and I speculate here as to how this could be done. Solar cells, batteries, and LEDs (light-emitting diodes) could be used, but have life cycles much shorter than the design life of the New Pharos. Radioactive decay isotopes like americium-241 made in a nuclear reactor can provide heat for thousands of years without maintenance, but currently require bi-metallic thermo-couples to convert the heat to electricity to power LEDs: again, such systems degrade and we do not know their life but I expect it to be relatively short. Another possibility is a phosphorescent material like strontium aluminate ($SrAl_2O_4$), which stores energy from light during the day and re-emits it during the night. We could apply this as paint or ceramic tiles but again we do not know the longevity of these materials. A final possibility is to drill a well somewhere in the delta to extract natural gas and pipe this to the top of the building. All these ideas are far from ideal, and until future technological developments provide a better solution, we may have to rely on a light source that needs regular maintenance.

Conclusions

I do not expect any of the Wonders to be rebuilt as I have described, but I have enjoyed speculating on how it could be done. It has given me a new insight into the challenges faced by the original builders and how advances in scientific knowledge lead us to better solutions to ancient problems. It also shows how we can try to design structures that will last for a very long time, whose presence may increase the stability of our societies.

References

1. Clayton, P.A. and M. Price, eds. 1988. *The Seven Wonders of the Ancient World*. Routledge: London.
2. Casson, L. 1994. *Travel in the Ancient World*. Johns Hopkins University Press: Baltimore.
3. Habicht, C. 1985. *Pausanias' Guide to Ancient Greece*. University of California Press: Berkeley.
4. Romer, J. and E. Romer. 1995. *The Seven Wonders of the World: A History of the Modern Imagination*. Henry Holt: New York.
5. Ashley, M. 1980. *The Seven Wonders of the World*. Fontana: London.
6. Kroll, W. 1941. "Philon 49." In *Realencyclopädie der classischen Altertumswissenschaften vol. XX1.* Stuttgart. Cols. 54–55.
7. Oleson, J.P., ed. 2008. *The Oxford Handbook of Engineering and Technology in the Classical World*. Oxford University Press: Oxford.
8. Wikander, Ö. 2008. "Sources of Energy and Exploitation of Power." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson, 136–157. Oxford University Press: Oxford.
9. Greene, K. 2000. "Technological Innovation and Economic Progress in the Ancient World: M. I. Finley Re-Considered." *The Economic History Review* 53(1): 29–59.
10. Goldberg, P., V.T. Holliday, and C.R. Ferring. 2001. *Earth Sciences and Archaeology*. Springer Science & Business Media: New York.
11. Bradley, R.S. 2017. *Paleoclimatology: Reconstructing Climates of the Quaternary*. Academic Press: Amsterdam.
12. Bird, P. 2003. "An Updated Digital Model of Plate Boundaries." *Geochemistry, Geophysics, Geosystems* 4(3): 1027.
13. Youngquist, W.L. 1997. *GeoDestinies: The Inevitable Control of Earth Resources Over Nations and Individuals*. National Book Co.: Portland, OR.
14. Durant, W.J. 1946. "What Is Civilization?" *Ladies' Home Journal* LXIII (January): 22, 103, 104, 107.
15. Bjornerud, M. 2020. *Timefulness: How Thinking Like a Geologist Can Help Save the World*. Princeton University Press: Princeton, NJ.

16. Piccardi, L. and W.B. Masse, eds. 2007. *Myth and Geology*. Geological Society: London.
17. Burbery, T.J. 2021. *Geomythology: How Common Stories Reflect Earth Events*. Routledge: London.
18. Mayor, A. 2000. *The First Fossil Hunters: Paleontology in Greek and Roman Times*. Princeton University Press: Princeton, NJ.
19. Hsü, K.J. 1983. *The Mediterranean Was a Desert: A Voyage of the Glomar Challenger*. Princeton University Press: Princeton, NJ.
20. Heckel, W. 2020. *In the Path of Conquest: Resistance to Alexander the Great*. Oxford University Press: Oxford.
21. Rink, W.J. and J.W. Thompson. 2015. *Encyclopedia of Scientific Dating Methods*. Springer: Netherlands.
22. Edwards, I.E.S. 1987. *The Pyramids of Egypt*. Penguin Books: Harmondsworth.
23. Lehner, M. and Z.A. Hawass. 2017. *Giza and the Pyramids*. Thames & Hudson Ltd: London.
24. Der Manuelian, P. 2017. *Digital Giza: Visualizing the Pyramids*. Harvard University Press: Cambridge, MA.
25. Rackham, H., W.H.S. Jones, and D.E. Eichholz, eds. 1947. *Pliny: Natural History*. Harvard University Press; W. Heinemann: Cambridge, MA; London.
26. Klemm, D.D. and R. Klemm. 2010. *The Stones of the Pyramids: Provenance of the Building Stones of the Old Kingdom Pyramids of Egypt*. De Gruyter: Berlin, Germany, New York.
27. Raynaud, S. et al. 2010. "Geological and Topographical Study of the Original Hills at the Base of Fourth Dynasty Egyptian Monuments of the Memphite Plateau." *Bulletin de la Societe Géologique de France* 181(3): 279–290.
28. Bunbury, J. and D. Jeffreys. 2011. "Real and Literary Landscapes in Ancient Egypt." *Cambridge Archaeological Journal* 21(1): 65–76.
29. Dash, G. 2015. "On the Field Testing of Methods the Egyptians May Have Used to Find Cardinal Directions." *Journal for the History of Astronomy* 46(3): 351–364.
30. Dash, G. 2012. "New Angles on the Great Pyramid." *Aeragram* 13: 10–19.
31. Morishima, K. et al. 2017. "Discovery of a Big Void in Khufu's Pyramid by Observation of Cosmic-Ray Muons." *Nature* 552(7685): 386–390.
32. Lehner, M. 2014. "On the Waterfront: Canals and Harbors in the Time of Giza Pyramid-Building." *AERAgram* 15: 14–23.
33. Howard Vyse, R.W.H. and J.S. Perring. 1840. *Operations Carried on at the Pyramids of Gizeh in 1837: With an Account of a Voyage into Upper Egypt, and an Appendix*. J. Fraser: London.

34. Reader, C.D. 2001. "A Geomorphological Study of the Giza Necropolis, with Implications for the Development of the Site." *Archaeometry* 43(1): 149–165.
35. Rossi, C. 2003. *Architecture and Mathematics in Ancient Egypt*. Cambridge University Press: Cambridge.
36. Herz-Fischler, R. 2009. *The Shape of the Great Pyramid*. Wilfrid Laurier University Press: Waterloo, Canada.
37. Collins, R.O. 2002. *The Nile*. Yale University Press: New Haven, CT.
38. Bunbury, J., K. Lutley, and A. Graham. 2009. "Giza Geomorphological Report in Giza Plateau Mapping Project Seasons 2006–2007 Preliminary Report." *Giza Occasional Papers* 3: 158–165.
39. Butzer, K.W., E. Butzer, and S. Love. 2013. "Urban Geoarchaeology and Environmental History at the Lost City of the Pyramids, Giza: Synthesis and Review." *Journal of Archaeological Science* 40(8): 3340–3366.
40. Bunbury, J. 2019. *The Nile and Ancient Egypt: Changing Land- and Waterscapes, from the Neolithic to the Roman Era*. Cambridge University Press: Cambridge.
41. Dash, G. 2017. "Occam's Egyptian Razor: The Equinox and the Alignment of the Pyramids." *The Journal of Ancient Egyptian Architecture* 2: 1–9.
42. Harrell, J.A. and P. Storemyr. 2009. "Ancient Egyptian Quarries–an Illustrated Overview." In *QuarryScapes: Ancient Stone Quarry Landscapes in the Eastern Mediterranean*, ed. N. Abu-Jaber et al., 7–50. Geological Survey of Norway, Special Publication: Oslo, Norway.
43. Harrell, J.A. and P. Storemyr. 2013. "Limestone and Sandstone Quarrying in Ancient Egypt: Tools, Methods, and Analogues." *Marmora: International Journal for Archaeology History and Archaeometry of Marbles and Stone* 9: 19–44.
44. Köhler, E.C., E. Hart, and M. Klaunzer. 2017. "Wadi el-Sheikh: A New Archaeological Investigation of Ancient Egyptian Chert Mines." *PLOS ONE* 12(2): e0170840.
45. Hemeda, S. and A. Sonbol. 2020. "Sustainability Problems of the Giza Pyramids." *Heritage Science* 8(1): 8.
46. Harrell, J.A. 2017. "Amarna Gypsite: A New Source of Gypsum for Ancient Egypt." *Journal of Archaeological Science: Reports* 11: 536–545.
47. Clarke, S. and R. Engelbach. 1930. *Ancient Egyptian Masonry: The Building Craft*. Oxford University Press, H. Milford: London.
48. Harrell, J.A. 2016. "Mapping the Tura-Masara Limestone Quarries." *Journal of the American Research Center in Egypt* 52: 199–214.
49. Stocks, D.A. 2003. "Immutable Laws of Friction: Preparing and Fitting Stone Blocks into the Great Pyramid of Giza." *Antiquity* 77(297): 572–578.

50. Stocks, D.A. 2003. *Experiments in Egyptian Archaeology: Stoneworking Technology in Ancient Egypt*. Routledge: London; New York.
51. Tallet, P. and G. Marouard. 2014. "The Harbor of Khufu on the Red Sea Coast at Wadi al-Jarf, Egypt." *Near Eastern Archaeology* 77(1): 4–14.
52. Hodges, P. and J. Keable. 1989. *How the Pyramids Were Built*. Element Books Ltd.: Longmead, UK.
53. Herodotus. 2003. *The Histories*. Penguin Classics: London.
54. Prevos P. 2010. "Desk Study of the Construction Logistics of the Pyramid of Khufu." Blog post. https://prevos.net/pyramid/construction/deskstudy/.
55. Smil, V. 2018. *Energy and Civilization: A History*. The MIT Press: Cambridge, MA.
56. Tawadros, E. 2001. *Geology of Egypt and Libya*. A.A. Balkema: Rotterdam.
57. Sampsell, B.M. 2003. *A Traveler's Guide to the Geology of Egypt*. The American University in Cairo Press: Cairo.
58. El-Bialy, M.Z. 2020. "Precambrian Basement Complex of Egypt." In *The Geology of Egypt*, ed. Z. Hamimi et al., 37–79. Springer: Cham.
59. Said, R. 2017. *The Geology of Egypt*. Routledge: London.
60. Kelany, A. et al. 2009. "Granite Quarry Survey in the Aswan Region, Egypt: Shedding New Light on Ancient Quarrying." In *QuarryScapes: Ancient Stone Quarry Landscapes in the Eastern Mediterranean*, ed. N. Abu-Jaber et al., 87–98. Geological Survey of Norway: Oslo, Norway.
61. Klemm, R. and D.D. Klemm. 2008. *Stones and Quarries in Ancient Egypt*. British Museum Press: London.
62. Middleton, A. and D. Klemm. 2003. "The Geology of the Rosetta Stone." *The Journal of Egyptian Archaeology* 89(1): 207–216.
63. Kelany, A., J.A. Harrell, and V.M. Brown. 2010. "Dolerite Pounders: Petrology, Sources and Use." *Lithic Technology* 35(2): 127–148.
64. Röder, J. 1965. *Zur Steinbrüchgeschichte de Rosengranits von Aswan*. Archäologischer Anzeiger. Jahrbuch des Deutschen Archäologischen Instituts. *Berlin* 3: 467–552.
65. Heldal, T. and P. Storemyr. 2015. "Fire on the Rocks: Heat as an Agent in Ancient Egyptian Hard Stone Quarrying." In *Engineering Geology for Society and Territory*—Volume 5, ed. G. Lollino et al., 291–295. Springer: Cham.
66. Davies, N.d.G. 1943. *The Tomb of Rekh-mi-re' at Thebes*. Publications of the Metropolitan Museum of Art Egyptian Expedition. Vol. 11, Metropolitan Museum of Art: New York.
67. Heldal, T. et al. 2016. "Gneiss for the Pharaoh: Geology of the Third Millennium BCE Chephren's Quarries in Southern Egypt." *Geoscience Canada* 43: 63–78.

68. Bloxam, E. 2000. "Transportation of Quarried Hard Stone from Lower Nubia to Giza during the Old Kingdom." In *Current Research in Egyptology 2000*, ed. A. McDonald and C. Riggs, 19–28. Archeopress: Oxford.
69. Cooper, J.P. 2011. "Humbler Craft: Rafts of the Egyptian Nile, 17th to 20th Centuries AD." *International Journal of Nautical Archaeology* 40(2): 344–360.
70. Hoffmeier, J.K. 1993. "The Use of Basalt in Floors of Old Kingdom Pyramid Temples." *Journal of the American Research Center in Egypt* 30: 117–123.
71. Mallory-Greenough, L.M., J.D. Greenough, and J.V. Owen. 2000. "The Origin and Use of Basalt in Old Kingdom Funerary Temples." *Geoarchaeology* 15(4): 315–330.
72. Edwards, H. et al. 2007. "Raman Spectroscopy of Natron: Shedding Light on Ancient Egyptian Mummification." *Analytical and Bioanalytical Chemistry* 388(3): 683–689.
73. Taher, A. 1999. "Inland Saline Lakes of Wadi El Natrun Depression, Egypt." *International Journal of Salt Lake Research* 8: 149–169.
74. Shortland, A.J. 2004. "Evaporites of the Wadi Natrun: Seasonal and Annual Variation and Its Implication for Ancient Exploitation." *Archaeometry* 46(4): 497–516.
75. Harrell, J.A. and M.D. Lewan. 2002. "Sources of Mummy Bitumen in Ancient Egypt and Palestine." *Archaeometry* 44(2): 285–293.
76. White, J. 1801. *Aegyptica: Or Observations on Certain Antiquities of Egypt*. Oxford.
77. Ray, J., ed. 1693. *A Collection of Curious Travels & Voyages in Two Tomes*. Printed for S. Smith and B. Walford: London.
78. Ambraseys, N., C.P. Melville, and R.D. Adams. 1994. *The Seismicity of Egypt, Arabia, and the Red Sea: A Historical Review*. Cambridge University Press: Cambridge; New York.
79. El-Sayed, A., F. Vaccari, and G.F. Panza. 2004. "The Nile Valley of Egypt: A Major Active Graben That Magnifies Seismic Waves." *Pure and Applied Geophysics* 161: 983–1002.
80. Lal Gauri, K., J.J. Sinai, and J.K. Bandyopadhyay. 1995. "Geologic Weathering and Its Implications on the Age of the Sphinx." *Geoarchaeology* 10(2): 119–133.
81. Simpson, W.K. and R.K. Ritner. 2003. *The Literature of Ancient Egypt: An Anthology of Stories, Instructions, and Poetry*. Yale University Press: New Haven CT; London.
82. Harrell, J.A. and P. Storemyr. 2009. "Ancient Egyptian Quarries—an Illustrated Overview." *Geological Survey of Norway Special Publication* 12: 7–50.

83. King, R.J. 2002. "Turquoise." *Geology Today* 18(3): 110–114.
84. Faryad, S.W. 2002. "Metamorphic Conditions and Fluid Compositions of Scapolite-Bearing Rocks from the Lapis Lazuli Deposit at Sare Sang, Afghanistan." *Journal of Petrology* 43(4): 725–747.
85. Shortland, A.J. 2012. *Lapis Lazuli from the Kiln: Glass and Glassmaking in the Late Bronze Age*. Leuven University Press: Leuven.
86. Dunn Friedman, F., G. Borromeo, and M. Leveque. 1998. *Gifts of the Nile: Ancient Egyptian Faience*. Thames and Hudson: London.
87. Spence, K. 2000. "Ancient Egyptian Chronology and the Astronomical Orientation of Pyramids." *Nature* 408(6810): 320–324.
88. Hornung, E.K.R.W.D. 2006. *Ancient Egyptian Chronology*. Brill: Leiden; Boston.
89. Martin, O., ed. 2016. *Old Kingdom Copper Tools and Model Tools*. Vol. 14. Archeopress Egyptology: Oxford.
90. El Sharkawi, M.A., M.M. El Aref, and A. Motelib. 1990. "Syngenetic and Paleokarstic Copper Mineralization in the Palaeozoic Platform Sediments of West Central Sinai, Egypt." In *Sediment-Hosted Mineral Deposits: Proceedings of a Symposium Held in Beijing, People's Republic of China, 30 July–4 August 1988*, ed. D. Lamb et al., 159–172. Blackwell Publishing Ltd.: Oxford.
91. Davidovits, J. and M. Morris. 1988. *The Pyramids: An Enigma Solved*. Hippocrene Books: New York.
92. Folk, R.T.L. and D.H. Campbell. 1992. "Are the Pyramids of Egypt Built of Poured Concrete Blocks?" *Journal of Geological Education* 40: 25–34.
93. Jana, D. 2007. "Evidence from Detailed Petrographic Examinations of Casing Stones from the Great Pyramid of Khufu, a Natural Limestone from Tura, and a Man-Made (Geopolymeric) Limestone." *Proceedings of the Twenty-Ninth Conference on Cement Microscopy*, 207–266. International Cement Microscopy Association: Toronto, Canada.
94. Dalley, S. 2013. *The Mystery of the Hanging Garden of Babylon: An Elusive World Wonder Traced*. Oxford University Press: Oxford.
95. Muntz, C. 2017. *Diodorus Siculus and the World of the Late Roman Republic*. Oxford University Press: Oxford.
96. Finkel, I.L. 1988. "The Hanging Gardens of Babylon." In *The Seven Wonders of the Ancient World*, ed. P.A. Clayton and M. Price, 38–58. Routledge: London.
97. Amante, C. and B.W. Eakins. 2009, *ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis*. NOAA Technical Memorandum NESDIS NGDC-24.

98. Finkel, I.L. and M.J. Seymour. 2008. *Babylon*. Oxford University Press: Oxford; New York.
99. Wilkinson, T.J. 2003. *Archaeological Landscapes of the Near East*. University of Arizona Press: Tucson.
100. Kennett, D.J. and J.P. Kennett. 2006. "Early State Formation in Southern Mesopotamia: Sea Levels, Shorelines, and Climate Change." *The Journal of Island and Coastal Archaeology* 1(1): 67–99.
101. Van de Mieroop, M. 2003. "Reading Babylon." *American Journal of Archaeology* 107(2): 257–275.
102. George, A.R. 1992. *Babylonian Topographical Texts*. Orientalia Lovaniensia Analecta. Vol. 40. Peeters Publishers: Leuven.
103. Reade, J. 2000. "Alexander the Great and the Hanging Gardens of Babylon." *Iraq* 62: 195–217.
104. George, A.R. 1993. "Babylon Revisited—Archaeology and Philology in Harness." *Antiquity* 67(257): 734–746.
105. Jones, F. 1854. "Art. V.—Topography of Nineveh, illustrative of the Maps of the chief cities of Assyria; and the general Geography of the country intermediate between the Tigris and the Upper Zab." *Journal of the Royal Asiatic Society* 15: 297–396.
106. Petit, L.P. and D.M. Bonacossie, eds. 2017. *Nineveh, the Great City*. Sidestone Press: Leiden.
107. Van De Mieroop, M. 2004. "A Tale of Two Cities: Nineveh and Babylon. *Iraq* 66: 1–5.
108. Madhloom, T.A. 1970. *The Chronology of Neo-Assyrian Art*. University: London.
109. Gadd, C.J. 1936. *The Stones of Assyria; the Surviving Remains of Assyrian Sculpture, Their Recovery, and Their Original Positions*. Chatto and Windus: London.
110. Russell, J.M. 1991. *Sennacherib's Palace without Rival at Nineveh*. University of Chicago Press: Chicago.
111. Layard, A.H. 1849. *Nineveh and its remains, with an account of a visit to the Chalaean Christians of Kurdistan, and the Yezidis, or devil-worshippers and an enquiry into the manners and arts of the ancient Assyrians*. John Murray: London.
112. Reade, J.E. 1998. *Assyrian Sculpture*. British Museum Press: London.
113. Layard, A.H. 1853. *A second series of the Monuments of Nineveh; including bas-reliefs from the palace of Sennacherib and bronzes from the ruins of Nimroud. From drawings made on the spot, during a second expedition to Assyria*. J. Murray: London.

114. Bianchetti, P.L. 2017. "Sennacherib's Quarries and the Stones of the Southwest Palace Decoration." In *Nineveh, the Great City*, ed. L.P. Petit and D.M. Bonacossie, 158–159. Sidestone Press: Leiden.
115. Dalley, S. 1994. "Nineveh, Babylon and the Hanging Gardens: Cuneiform and Classical Sources Reconciled." *Iraq* 56: 45–58.
116. Ur, J. 2005. Sennacherib's Northern Assyrian Canals: New Insights from Satellite Imagery and Aerial Photography." *Iraq* 67(1): 317–345.
117. Jacobsen, T. and S. Lloyd. 1935, *Sennacherib's Aqueduct at Jerwan*. The University of Chicago Press: Chicago, 52.
118. Al-Shaikh, Z.D. 1975. "The Mosul-Hammam Al-Alil Fault and Its Possible Relations to the Mineral Springs of the Area." *Journal of the Geological Society of Iraq* Special Issue: 69–78.
119. Nabeel, K.A.-A. 2013. "Paleo and Neo-Tectonics of the Mosul Fault and Its Impact on the Tectonics of the Foreland Area of Iraq." *Iraqi National Journal of Earth Sciences* 13(1): 59–74.
120. Middlemiss, F.A., A.A. Moss, and G.F. Claringbull. 1953. "The Stone of the Ancient Assyrian Monumental Carvings." *Geological Magazine* 90(2): 141.
121. Mitchell, T.C. and A.P. Middleton. 2002. "The Stones Used in the Assyrian Sculptures." *Journal of Cuneiform Studies* 54: 93–98.
122. Sinha, A. et al. 2019. "Role of Climate in the Rise and Fall of the Neo-Assyrian Empire." *Science Advances* 5(11): eaax6656.
123. Morozova, G.S. 2005. "A Review of Holocene Avulsions of the Tigris and Euphrates Rivers and Possible Effects on the Evolution of Civilizations in Lower Mesopotamia." *Geoarchaeology* 20(4): 401–423.
124. King, L.W. 1915. *Bronze Reliefs from the Gates of Shalmaneser, King of Assyria B.C. 860–825*. British Museum: London.
125. Issar, A. 1990. *Water Shall Flow from the Rock: Hydrogeology and Climate in the Lands of the Bible*. Springer-Verlag: Berlin; New York.
126. Montgomery, D.R. 2007. *Dirt: The Erosion of Civilizations*. University of California Press: Berkeley.
127. Jassim, S.Z. and J.C. Goff. 2006. *Geology of Iraq*. Dolin; Moravian Museum: Prague; Brno.
128. Fitz, S. 1982. "The Colored Glazes of Neo-Babylonian Wall Facings." *Ceramic Forum International* 59: 179–185.
129. Rodler, A.S. et al. 2019. "Probing the Provenance of Archaeological Glaze Colorants: Polychrome Faunal Reliefs of the Ishtar Gate and the Processional Way of Babylon. *Archaeometry* 61(4): 837–855.
130. Yalçın, Ü. 2017. "The Beginnings of Metal Use in West Asia." In *Ancient West Asian Civilization: Geoenvironment and Society in the Pre-Islamic*

Middle East, ed. A. Tsuneki, S. Yamada, and K.-I. Hisada, 115–130. Springer Singapore: Singapore.
131. Matin, M. and A.M. Pollard. 2017. "From Ore to Pigment: A Description of the Minerals and an Experimental Study of Cobalt Ore Processing from the Kāshān Mine, Iran." *Archaeometry* 59(4): 731–746.
132. Siculus, D. 2014. *The Library of History*. Harvard University Press: Cambridge, MA.
133. Schwartz, M., D. Hollander, and G. Stein. 1999. "Reconstructing Mesopotamian Exchange Networks in the 4th Millennium BC: Geochemical and Archaeological Analyses of Bitumen Artifacts from Hacinebi Tepe, Turkey." *Paléorient* 25(1): 67–82.
134. Connan, J. and T. Van de Velde. 2010. "An Overview of Bitumen Trade in the Near East from the Neolithic (c.8000 BC) to the Early Islamic Period." *Arabian Archaeology and Epigraphy* 21(1): 1–19.
135. Sorkhabi, R. 2010. "Why So Much Oil in the Middle East?" *GeoExplo* 7(1): 21–26.
136. Bell, G.L. 1911. *Amurath to Amurath*. William Heinemann: London.
137. Bilkadi, Z. 1984. "Bitumen—A History." *Aramco World Magazine* (6): 2–9.
138. Alsharhan, A.S. and A.E.M. Nairn. 1997. *Sedimentary Basins and Petroleum Geology of the Middle East*. Elsevier: Amsterdam; New York.
139. Sorkhabi, R. 2010. "Oil from Babylon to Iraq." *GeoExplo* 6(2): 56–60.
140. Nováček, K. et al. 2021. *Mosul after Islamic State: The Quest for Lost Architectural Heritage*. Palgrave Macmillan: Cham, Switzerland.
141. Reade, J. 2017. "The Assyrian Palace at Nabi Yunus, Nineveh." In *At the Dawn of History*, ed. H. Yağmur, S. Adam, and W. Martin, 431–458. Penn State University Press: Philadelphia.
142. Liverani, M. 2016. *Imagining Babylon: The Modern Story of an Ancient City*. De Gruyter: Berlin.
143. Scurlock, J. 2006. *Magico-Medical Means of Treating Ghost-Induced Illnesses in Ancient Mesopotamia*. Brill / Styx: Leiden; Boston.
144. Oleson, J.P. 2000. "Water-Lifting." In *Handbook of Ancient Water Technology*, ed. Ö. Wikander, 217–302. Brill: Leiden.
145. Dalley, S. and J.P. Oleson. 2003. "Sennacherib, Archimedes, and the Water Screw: The Context of Invention in the Ancient World." *Technology and Culture* 44(1): 1–26.
146. Kvenvolden, K.A. and C.K. Cooper. 2003. "Natural Seepage of Crude Oil into the Marine Environment." *Geo-Marine Letters* 23(3–4): 140–146.
147. Nissenbaum, A. 1978. "Dead Sea Asphalts; Historical Aspects." *AAPG Bulletin* 62(5): 837–844.

148. Hammond, P.C. 1959. "The Nabataean Bitumen Industry at the Dead Sea." *The Biblical Archaeologist* 22(2): 40–48.
149. Nissenbaum, A. 1993. "The Dead Sea—an Economic Resource for 10,000 Years." *Hydrobiologia* 267(1): 127–141.
150. Swaddling, J. 1980. *The Ancient Olympic Games*. British Museum Publications: London.
151. Maran, J. 2016. "The Persistence of Place and Memory: The Case of the Early Helladic Rundbau and the Mycenaean Palatial Megara of Tiryns." In *Von Baden bis Troia: Ressourcennutzung, Metallurgie und Wissenstransfer*, ed. M. Bartelheim, B. Horejs, and R. Krauss, 153–173. Verlag Marie Leidorf: Rahden, Germany.
152. Patay-Horvath, A. 2020. "The Evolution of the Sacred Landscape of Early Olympia." In *Experiencing the Landscape in Antiquity*, ed. A. Cristilli, A. Gonfloni, and F. Stok, 167–171. BAR Publishing: Oxford.
153. Price, M. 1988. "The Statue of Zeus at Olympia." In *The Seven Wonders of the Ancient World*, ed. P.A. Clayton and M. Price, 59–77. Routledge: London.
154. Lapatin, K.D.S. 2001. *Chryselephantine Statuary in the Ancient Mediterranean World*. Oxford University Press: New York.
155. Boetticher, A. 1886. *Olympia, das Fest und seine Stätte*. Verlag von Julius Springer: Berlin.
156. Seltman, C.T. 1952. "The Wardrobe of Artemis." *The Numismatic Chronicle and Journal of the Royal Numismatic Society* 12: 33–51.
157. Berk, H.J. 2018. *100 Greatest Ancient Coins*. Whitman Publishing: Florence, Alabama.
158. Adler, F., E. Curtius, and G. Treu. 1897. *Olympia: die Ergebnisse der von dem Deutschen Reich veranstalteten Ausgrabung im Auftrage des Königlich Preußischen Ministers der geistlichen Unterrichts- und Medicinal-Angelegenheiten*. Asher: Berlin.
159. Patay-Horváth, A. 2019. "Greek Temple Building from an Economic Perspective: Case Studies from the Western Peloponnesos." In *New Directions and Paradigms for the Study of Greek Architecture*, ed. P. Sapirstein and D. Scahill, 168–177. Brill: Leiden.
160. Morfis, A. and H. Zojer. 1985. "Karst Hydrogeology of the Central and Eastern Peloponnesus (Greece)." *Steirische Beiträge zur Hydrogeologie* 37: 1–301.
161. Fountoulis, I., I. Mariolakos, and I. Ladas. 2014. "Quaternary Basin Sedimentation and Geodynamics in SW Peloponnese (Greece) and Late Stage Uplift of Taygetos Mt." *Bollettino di Geofisica Teorica ed Applicata* 55(2): 303–324.

162. Fountoulis, I. and I. Mariolakos. 2008. "Neotectonic Folds in the Central-Western Peloponnese, Greece." *Zeitschrift der Deutschen Gesellschaft fur Geowissenschaften* 159(3): 485.
163. Retallack, G.J. 2008. "Rocks, Views, Soils and Plants at the Temples of Ancient Greece." *Antiquity* 82(317): 640–657.
164. Fouache, E. and K. Pavlopoulos. 2010. "The Interplay between Environment and People from Neolithic to Classical Times in Greece and Albania." In *Landscapes and Societies: Selected Cases*, ed. I.P. Martini and W. Chesworth, 155–166. Springer: Dordrecht.
165. Ford, D. and P.D. Williams. 2007. *Karst Hydrogeology and Geomorphology*. John Wiley & Sons: Chichester, UK.
166. LaMoreaux, P. and J. LaMoreaux. 2007. "Karst: The Foundation for Concepts in Hydrogeology." *Environmental Geology* 51(5): 685–688.
167. Clendenon, C. 2009. "Ancient Greek Hydromyths about the Submarine Transport of Terrestrial Fresh Water through Seabeds Offshore of Karstic Regions." *Acta Carsologica* 38: 293–302.
168. Glaser, F. 2000. "Fountains and Nymphaea." In *Handbook of Ancient Water Technology*, ed. Ö. Wikander, 414–451. Brill: Leiden, Boston.
169. Ustinova, Y. 2009. *Caves and the Ancient Greek Mind: Descending Underground in the Search for Ultimate Truth*. Oxford University Press: Oxford.
170. Higgins, M.D. and R. Higgins. 1996. *A Geological Companion to Greece and the Aegean*. Cornell University Press / Duckworth Publishers: Ithaca, NY / London.
171. Thornton, M. 1975. *Dredging for Gold: The Gold Divers' Handbook: An Illustrated Guide to the Hobby of Underwater Gold Prospecting*. Keene Industries: Northridge, CA.
172. Southam, G. et al. 2009. "The Biogeochemistry of Gold." *Elements* 5(5): 303–307.
173. Topkaya, Y. 1984. "Recent Evaluation of Sart Placer Gold Deposit." In *Precious Metals: Mining, Extraction and Processing*, ed. V. Kudryk, D.A. Corrigan and W.W. Liang, 111–121. American Institute of Mining, Metallurgical, and Petroleum Engineers: New York.
174. Su, X.W. and F.Z. Cui. 1999. "Hierarchical Structure of Ivory: From Nanometer to Centimeter." *Materials Science and Engineering: C.* 7(1): 19–29.
175. Lapatin, K.D.S. 1997. "Pheidias ἐλεφαντουργός." *American Journal of Archaeology*. 101(4): 663–682.
176. Stern, E.M. 2008. "Glass Production." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. P.T. Craddock and M.J. Hughes, 520–548. Oxford University Press: Oxford.

177. Henderson, J. 2013. *Ancient Glass*. Cambridge University Press: Cambridge.
178. Rasmussen, S.C. 2015. "Modern Materials in Antiquity: An Early History of the Art and Technology of Glass." In *Chemical Technology in Antiquity*, ed. S.C. Rasmussen, 267–313. American Chemical Society.
179. Tsampiri, M. 2018. "Obsidian in the Prehistoric Aegean: Trade and Uses." *Bulletin of the Geological Society of Greece* 53(1): 28–49.
180. Freestone, I.C. 2008. "Pliny on Roman Glassmaking." In *Archaeology, History and Science: Integrating Approaches to Ancient Materials*, ed. M. Martinón-Torres and T. Rehren, 77–100. Left Coast Press: Walnut Creek, CA.
181. Brems, D. et al. 2012. "Western Mediterranean Sand Deposits as a Raw Material for Roman Glass Production." *Journal of Archaeological Science* 39(9): 2897–2907.
182. Freestone, I., Y. Gorin-Rosen, and M.J. Hughes. 2000. "Primary Glass from Israel and the Production of Glass in Late Antiquity and the Early Islamic Period." In *La Route de Verre*, ed. M.-D. Nenna, 65–83. Maison d'Orient: Lyon, France.
183. Bassett, S.G. 2000. "'Excellent Offerings': The Lausos Collection in Constantinople." *The Art Bulletin* 82(1): 6–25.
184. Mango, C., M. Vickers, and E.D. Francis. 1992. "The Palace of Lausus at Constantinople and Its Collection of Ancient Statues." *Journal of the History of Collections* 4(1): 89–92.
185. Ambraseys, N.N. 2009. *Earthquakes in the Mediterranean and Middle East: A Multidisciplinary Study of Seismicity up to 1900*. Cambridge University Press: Cambridge; New York.
186. Alexandris, A., I. Psycharis, and E. Protopapa. 2014. "The Collapse of the Ancient Temple of Zeus at Olympia Revisited." In *Second European Conference on Earthquake Engineering and Seismology*, 1–12. Istanbul, Turkey.
187. Fouache, E. 1999. "L'alluvionnement historique en Grece occidentale et au Peloponnese." *Bulletin de correspondance hellénique—Supplement* 35: 235.
188. Scheffers, A. et al. 2008. "Late Holocene Tsunami Traces on the Western and Southern Coastlines of the Peloponnesus (Greece)." *Earth and Planetary Science Letters* 269(1–2): 271–279.
189. Papadopoulos, G.A. and B.J. Chalkis. 1984. "Tsunamis Observed in Greece and the Surrounding Area from Antiquity Up to the Present Times." *Marine Geology* 56: 309–317.

190. Büntgen, U. et al. 2016. "Cooling and Societal Change during the Late Antique Little Ice Age from 536 to around 660 AD." *Nature Geoscience* 9(3): 231–236.
191. Woodward, J.C. 2009. *The Physical Geography of the Mediterranean*. Oxford University Press: Oxford; New York.
192. Curtius, E., G. Hirschfeld, and F. Adler. 1876. *Die Ausgrabungen zu Olympia. XXII Tafeln in Lichtdruckt Band 1*. Verlag von Ernst Wasmuth: Berlin.
193. Chandler, R. 1776. *Travels in Greece, or an Account of a Tour Made at the Expense of the Society of Dilettanti, by Richard Chandler*. Clarendon Press: Oxford.
194. Fountoulis, I. et al. 2013. "Shoreline Displacement and Pineios River Diversions in NW Peloponnese (Greece) as Result of the Geology, Active Tectonics and Human Activity during the last 100 ky." *Zeitschrift fur Geomorphologie*, Supplementary Issues 57(3): 97–123.
195. Clendenon, C. 2009. "Karst Hydrology in Ancient Myths from Arcadia and Argolis, Greece. *Acta Carsologica*. 38: 145–154.
196. Robinson, B.A. 2019." The Prospect from the Watershed: Places and Poetics, Figures and Narratives." In *Ancient Waterlands*, ed. B.A. Robinson, S. Collin Bouffier, and I. Fumadó Ortega, 15–34. Presses Universitaires de Provence: Aix-en-Provence.
197. Vlachos, E. et al. 2018. "The Paradise Lost of Milia (Grevena, Greece; Late Pliocene, Early Villafranchian, MN15/MN16a): Faunal Composition and Diversity." *Quaternary* 1(2): 13.
198. Pedersen, P. 2013. "The 4th century BC 'Ionian Renaissance' and Karian Identity." *Publications de l'Institut Français d'Études Anatoliennes* 28(1): 33–64.
199. Bernoulli, D., P.C. De Graciansky, and O. Monod. 1974. "The Extension of the Lycian Nappes (SW Turkey) into the Southeastern Aegean Islands." *Eclogae Geologicae Helvetiae* 67(1): 39–90.
200. Masse, J.-P. et al. 2015. "Berriasian rudist faunas and micropalaeontology of Stramberk type carbonate exotics from the Lycian nappes, Bodrum Peninsula, southwest Turkey." *Cretaceous Research* 56: 76–92.
201. Poulsen, B. 2016. "The Necropolis Outside the Myndos Gate in Halikarnassos-M and Mosaics." In *Death and Burial in Karia. Halicarnassian Studies VI*, ed. E. Mortensen and B. Poulsen, 11–108. Syddansk Universitetsforlag.
202. van Bremen, R. and J.-M. Carbon. 2010. *Hellenistic Karia*. Ausonius-Publications.

203. Jenkins, I. 2010. "The Mausolea of Halicarnassus." *Bulletin of the Institute of Classical Studies*. Supplement 56(104): 121–135.
204. Walker, S. and K.J. Matthews. 1997. "The Marbles of the Mausoleum." In *Sculptors and Sculpture of Caria and the Dodecanese*, ed. I. Jenkins and G.B. Waywell, 49–59. British Museum Press: London.
205. Waywell, G.B. 1978. *The Free-Standing Sculptures of the Mausoleum at Halicarnassus in the British Museum*. British Museum Publications: London.
206. Attanasio, D., M. Brilli, and M. Bruno. 2008. "The Properties and Identification of Marble from Proconnesos (Marmara Island, Turkey): A New Database Including Isotopic, EPR and Petrographic Data. *Archaeometry* 50(5): 747–774.
207. Russell, B. 2014. *The Economics of the Roman Stone Trade*. Oxford University Press: Oxford.
208. de Callataÿ, F. 2005. "The Graeco-Roman Economy in the Super Long-Run: Lead, Copper, and Shipwrecks." *Journal of Roman Archaeology* 18: 361–372.
209. Jenkins, I., C. Gratziu, and A.P. Middleton. 1997. "The Polychromy of the Mausoleum." In *Sculptors and Sculpture of Caria and the Dodecanese*, ed. I. Jenkins and G.B. Waywell, 35–41. British Museum Press: London.
210. Brinkmann, V. 2008. "The Polychromy of Ancient Greek Sculpture." In *The Color of Life: Polychromy in Sculpture from Antiquity to the Present*, ed. K.D.S. Lapatin, R. Panzanelli, and E.D. Schmidt, 18–39. J. Paul Getty Museum: Los Angeles.
211. Jeppesen, K. and I. Zahle. 1973. "The Site of the Mausoleum at Halicarnassus Reexcavated." *American Journal of Archaeology* 77(3): 336–338.
212. Ulusoy, I. et al. 2004. "Volcanic and Deformation History of the Bodrum Resurgent Caldera System (Southwestern Turkey)." *Journal of Volcanology and Geothermal Research* 136: 71–96.
213. Bean, G.E. and J.M. Cook. 1955. "The Halicarnassus Peninsula." *The Annual of the British School at Athens* 50: 85–171.
214. Attanasio, D., M. Brilli, and N. Ogle. 2006. *The Isotopic Signature of Classical Marbles*. L'Erma di Bretschneider: Roma.
215. Fant, J.C. 2008. "Quarrying and Stoneworking." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson, 121–135. Oxford University Press: Oxford.
216. Palagia, O. 2006. *Greek Sculpture: Function, Materials, and Techniques in the Archaic and Classical Periods*. Cambridge University Press: New York.

217. Jaksch, H. et al. 1983. *Egyptian Blue—Cuprorivaite a Window to Ancient Egyptian Technology*. *Naturwissenschaften* 70(11): 525–535.
218. Berrie, B.H. 2012. *Rethinking the History of Artists' Pigments through Chemical Analysis*. *Annual Review of Analytical Chemistry* 5(1): 441–459.
219. Koukouli-Chrysanthaki, C. and G. Weisgerber. 1999. "Ochre Mines on Thasos." In *Thasos: Matieres premieres et technologie de la prehistoire a nos jours*, ed. C. Koukouli-Chrysanthaki, A. Muller, and S. Papadopoulos, 129–144. EFA-IH'EITKA: Athens.
220. Gifford, J.A. 2000. "Geological Aspects of the Construction of the Mausoleum at Halicarnassus." In *The Maussolleion at Halikarnassos. Volume 4: The Quadrangle. The Foundations of the Maussolleion and Its Sepulchral Compartments*, ed. K. Jeppesen, 144–149 .Aahus, Denmark.
221. Guidoboni, E. and A. Comastri. 1997. "The Large Earthquake of 8 August 1303 in Crete: Seismic Scenario and Tsunami in the Mediterranean Area." *Journal of Seismology* 1(1): 55–72.
222. Arbel, B. and A. Luttrell. 1996. "Plundering Ancient Treasures at Bodrum (Halicarnassus): A Commercial Letter Written on Cyprus, January 1507. *Mediterranean Historical Review* 11(1): 79–86.
223. Newton, C.T. and R.P. Pullan. 1862. *A History of Discoveries at Halicarnassus, Cnidus & Branchiae*. Day & son: London.
224. Fowler, F.G. and H.W. Fowler. 1939. *The Works of Lucian of Samosata*. Clarendon Press: Oxford.
225. Klein, N.L. 2016. "How Buildings Were Constructed." In *A Companion to Greek Architecture*, ed. M.M. Miles, 211–233. Wiley: UK.
226. Pierattini, A. 2018. "Early Greek Stone Construction and the Invention of the Crane." In *Building Knowledge, Constructing Histories*, eds. I. Wouters, et al., 1056–1060. CRC Press: London.
227. Carlson, D.N. 2016. "The Underwater Recovery of Monumental Marble Column Drums from an Ancient Shipwreck at Kızılburun, Turkey." *Journal of Maritime Archaeology* 11(2): 219–230.
228. Craddock, P.T. 2010. *Early Metal Mining and Production*. Archetype Publications Ltd: London.
229. Hauptmann, A. 2020. *Archaeometallurgy—Materials Science Aspects*. Springer International Publishing: Cham.
230. Scott, D.A. and R. Schwab. 2019. *Metallography in Archaeology and Art*. Springer: Cham.
231. Craddock, P.T. 2008. "Mining and Metallurgy." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson, 93–120. Oxford University Press: Oxford.

232. Voudouris, P. et al. 2019. "Gemstones of Greece: Geology and Crystallizing Environments." *Minerals* 9(8): 461.
233. Voudouris, P. et al. 2019. "Gem Corundum Deposits of Greece: Geology, Mineralogy and Genesis." *Minerals* 9(1): 49.
234. Papastamatiou, I.N. 1951. "The Emery of Naxos." In *The Mineral Wealth of Greece*, 37–69. Institute of Geological and Subsurface Research: Athens.
235. Bammer, A. 1974. "Recent Excavations at the Altar of Artemis in Ephesus". *Archaeology* 27(3): 202–205.
236. Muss, U. 2008. *Die archäologie der ephesischen Artemis: Gestalt und ritual eines Heiligtums*. Phoibos: Wien.
237. Wood, J.T. 1877. *Discoveries at Ephesus, including the site and remains of the great temple of Diana*. Longmans, Green and Co: London.
238. Bammer, A. 1972. *Die Architektur des jüngeren Artemision von Ephesos*. F. Steiner: Wiesbaden.
239. Kerschner, M. 2015. *Der Ursprung des Artemisions von Ephesos als Naturheiligtum. Naturmale als kultische Bezugspunkte in den großen Heiligtümern Ioniens*, ed. K. Sporn, S. Ladstätter, and M. Kerschner, 187–243. Natur–Kult–Raum. Akten des internationalen Kolloquiums.
240. LiDonnici, L.R. 1992. "The Images of Artemis Ephesia and Greco-Roman Worship: A Reconsideration." *Harvard Theological Review* 85(4): 389–415.
241. Zabrana, L. 2019. "The Artemision in the Roman Era: New Results of Research within the Sanctuary of Artemis." In *Religion in Ephesos Reconsidered: Archaeology of Spaces, Structures, and Objects*, ed. D.N. Schowalter, S.J. Friesen, S. Ladstätter, and C.M. Thomas, 158–170. Brill: Leiden.
242. Bammer, A. and U. Muss. 2006. "Water Problems in the Artemision of Ephesus. In *Cura Aquarum in Ephesus: Proceedings of the Twelfth International Congress on the History of Water Management and Hydraulic Engineering in the Mediterranean Region, Ephesus/Selçuk, Turkey, October 2–10, 2004*, ed. G. Wiplinger, 61–64. Peeters: Dudley, USA.
243. Bammer, A. 1990. "A 'Peripteros' of the Geometric Period in the Artemision of Ephesus." *Anatolian Studies* 40: 137–160.
244. Vitruvius, P., 1962. *On Architecture, edited by Frank Stephen Granger.* Harvard University Press: Cambridge, MA.
245. Brückner, H. et al. 2017. "Life Cycle of Estuarine Islands—From the Formation to the Landlocking of Former Islands in the Environs of Miletos and Ephesos in Western Asia Minor (Turkey)." *Journal of Archaeological Science: Reports* 12: 876–894.

246. Yavuz, A.B., M. Bruno, and D. Attanasio. 2011. "An Updated, Multi-method Database of Ephesus Marbles, Including White, Greco Scritto and Bigio Varieties." *Archaeometry* 53(2): 215–240.
247. Vött, A., H. Brückner, and J.C. Kraft. 2017. "Do Mythological Traditions Reflect Past Geographies? The Acheloos Delta (Greece) and the Artemision (Turkey) Case Studies." *Zeitschrift fur Geomorphologie* Supplementary Issue 61(1): 203–221.
248. Öziş, Ü., A. Atalay, and Y. Özdemir. 2014. "Hydraulic Capacity of Ancient Water Conveyance Systems to Ephesus." *Water Supply* 14(6): 1010–1017.
249. Stewart, I.S. and L. Piccardi. 2017. "Seismic Faults and Sacred Sanctuaries in Aegean Antiquity." *Proceedings of the Geologists' Association* 128(5–6): 711–721.
250. Sümer, Ö. 2015. "Evidence for the Reactivation of a Pre-existing Zone of Weakness and Its Contributions to the Evolution of the Küçük Menderes Graben: A Study on the Ephesus Fault, Western Anatolia, Turkey." *Geodinamica Acta* 27(2–3): 130–154.
251. Scherrer, P.G., L. Bier, and G.M. Luxon. 2000. *Ephesus: The New Guide*. Ege Yayinlari: Istanbul.
252. Kerschner, M. and W. Prochaska. 2011. "Die Tempel und Altäre der Artemis in Ephesos und ihre Baumaterialien." *Jahreshefte des Österreichischen archäologischen Institutes in Wien* 80: 73–154.
253. Bammer, A., L. Moens, and U. Muss. 2013. "The Geological Background of the Architecture in the Artemision of Ephesus." *Anatolia antiqua* 21(1): 93–102.
254. Dodge, H. 1988. "Decorative Stones for Architecture in the Roman Empire." *Oxford Journal of Archaeology* 7(1): 65–80.
255. Maniatis, Y., N. Herz, and Y. Basiakos, eds. 1995. *The Study of Marble and Other Stones Used in Antiquity: Asmosia III, Athens: Transactions of the 3rd International Symposium of the Association for the Study of Marble and Other Stones Used in Antiquity*. Archetype: London.
256. Ring, U. et al. 2007. "Early Exhumation of High-Pressure Rocks in Extrusion Wedges: Cycladic Blueschist Unit in the Eastern Aegean, Greece, and Turkey." *Tectonics* 26(2): TC2001.
257. D'Orazio, M. 2007. "Meteorite Records in the Ancient Greek and Latin Literature: between History and Myth." In *Myth and Geology*, ed. L. Piccardi and W.B. Masse, 215–225. Geological Society Special Publication. Geological Society of London: UK.
258. McBeath, A. and A.D. Gheorghe. 2005. "Meteor Beliefs Project: Meteorite Worship in the Ancient Greek and Roman Worlds." *WGN, Journal of the International Meteor Organization* 33(5): 135–144.

259. Rogers, G.M. 2012. *The Mysteries of Artemis of Ephesos: Cult, Polis, and Change in the Graeco-Roman World*. Yale University Press: New Haven, CT.
260. Burke, J.G. 1986. *Cosmic Debris: Meteorites in History*. University of California Press: Berkeley.
261. Norton, O.R. 2002. *The Cambridge Encyclopedia of Meteorites*. Cambridge University Press: Cambridge; New York.
262. Brückner, H. 2005. "Holocene Shoreline Displacements and Their Consequences for Human Societies: The Example of Ephesus in Western Turkey." *Zeitschrift fur Geomorphologie* 137(Suppl.): 11–22.
263. Stock, F. et al. 2013. "In Search of the Harbours: New Evidence of Late Roman and Byzantine Harbours of Ephesus. *Quaternary International* 312: 57–69.
264. Kraft, J.C. et al. 2007. "The Geographies of Ancient Ephesus and the Artemision in Anatolia." *Geoarchaeology* 22(1): 121–149.
265. Stock, F. et al. 2014. "The Palaeogeographies of Ephesos (Turkey), Its Harbours, and the Artemision: A Geoarchaeological Reconstruction for the Timespan 1500–300 BC. *Zeitschrift fur Geomorphologie* Supplementary Issue 58(2): 33–66.
266. Kraft, J.C. et al. 2011. "Results of the Struggle at Ancient Ephesus: Natural Processes 1, Human Intervention 0." *Geological Society,* London, Special Publication 352(1): 27–36.
267. Evelpidou, N., A. Karkani, and I. Kampolis. 2021. "Relative Sea Level Changes and Morphotectonic Implications Triggered by the Samos Earthquake of 30th October 2020." *Journal of Marine Science and Engineering* 9(1): 40.
268. Wiplinger, G. 2019. "De Aquaeductu Urbis Ephesi. Water for Roman Ephesus." 13th Babesch Lecture, The Babesch Foundation.
269. Robinson, B.A. 2017. "Fountains as Reservoirs of Myth and Memory." In *Myths on the Map*, ed. G. Hawes, 178–203. Oxford University Press: Oxford.
270. Guidoboni, E., A. Comastri, and G. Traina. 1994. "Catalogue of Ancient Earthquakes in the Mediterranean Area Up to the 10th Century." *Istituto nazionale di geofisica*: Rome.
271. Karwiese, S. 1995. *Gross ist die Artemis von Ephesos: die Geschichte einer der grossen Städt der Antike*. Phoibos Verlag: Vienna.
272. Muss, U. 2016. "The Artemision in Early Christian Times." *Early Christianity* 7(3): 293–312.
273. Van Alfen, P.G. et al., eds. 2020. *White Gold: Studies in Early Electrum Coinage*. The American Numismatic Society: New York.

274. Ramage, A., P.T. Craddock, and M.R. Cowell. 2000. *King Croesus' Gold: Excavations at Sardis and the History of Gold Refining*. British Museum Press: London.
275. Celauro, A., D. Loepp, and D. Ferro. 2017. "Ancient Procedures of Gold Cementation and Gold Scorification: Considerations on Their Reliability through Experimental Archaeology, Interpretation of Chemical Reactions and Thermodynamics." *Acta rerum naturalium* 21: 177–200.
276. Rehren, T. 2003. "Crucibles as Reaction Vessels in Ancient Metallurgy." In *Mining and Metal Production through the Ages*, ed. P. Craddock and J. Lang, 207–215. British Museum Press: London.
277. Kreemer, C. and N. Chamot-Rooke. 2004. "Contemporary Kinematics of the Southern Aegean and the Mediterranean Ridge." *Geophysical Journal International* 157(3): 1377–1392.
278. Dewey, J.F. and A.M.C. Şengor. 1979. "Aegean and Surrounding Regions: Complex Multiplate and Continuum Tectonics in a Convergent Zone." *Geological Society of America Bulletin* 90(1): 84–92.
279. Price, M.T. 2007. *Decorative Stone: The Complete Sourcebook*. Thames & Hudson: London.
280. Attanasio, D. et al. 2017. "Ancient 'Black' Decorative Stones and the Ephesian Origin of Sculptural bigio antico." *Archaeometry* 59(5): 794–814.
281. Galetti, G., L. Lazzarini, and M. Maggetti. 1992. "A First Characterization of the Most Important Granites Used in Antiquity." In *Ancient Stones: Quarrying, Trade and Provenance-Interdisciplinary Studies on Stones and Stone Technology in Europe and Near East from the Prehistoric to the Early Christian Period*, ed. M. Waelkens, N. Herz, and L. Moens, 167–177. Leuven University Press: Belgium.
282. Hartmann, W.K. 2015. "Chelyabinsk, Zond IV, and a Possible First-Century Fireball of Historical Importance." *Meteoritics & Planetary Science* 50(3): 368–381.
283. Fleming, K. et al. 1998. "Refining the Eustatic Sea-Level Curve since the Last Glacial Maximum Using Far- and Intermediate-Field Sites." *Earth and Planetary Science Letters* 163(1): 327–342.
284. Orschiedt, J. 2020. "Violence in Palaeolithic and Mesolithic Hunter-Gatherer Communities." In *The Cambridge World History of Violence: Volume 1: The Prehistoric and Ancient Worlds*, ed. G.G. Fagan et al., 58–78. Cambridge University Press: Cambridge.
285. Morhange, C. and N. Marriner. 2010. "Mind the (Stratigraphic) Gap: Roman Dredging in Ancient Mediterranean Harbours." *Bollettino di Archeologia Online* 1: 23–32.

286. Passchier, C.W. et al. 2013. "Normal Fault Displacement Dislocating a Roman Aqueduct of Ephesos, Western Turkey." *Terra Nova* 25(4): 292–297.
287. Ehrman, B.D. and Z. Plese. 2011. *The Apocryphal Gospels: Texts and Translations*. Oxford University Press: New York.
288. Sala, R., E. Garcia, and R. Tamba. 2012. "Archaeological Geophysics—from Basics to New Perspectives." In *Archaeology, New Approaches in Theory and Techniques*, ed. I. Ollich-Castanyer, 133–166. IntechOpen.
289. Gabrielsen, V. 1997. *The Naval Aristocracy of Hellenistic Rhodes*. Aarhus University Press: Aarhus.
290. Higgins, R.A. 1988. "The Colossus of Rhodes." In *The Seven Wonders of the Ancient World*, ed. P.A. Clayton and M. Price, 124–137. Routledge: London.
291. Vedder, U. 2017. "Was the Colossus of Rhodes Cast in Courses or in Large Sections?" In *Artistry in Bronze*, ed. J.M. Daehner, K. Lapatin, and A. Spinelli, 21–27. J. Paul Getty Museum and the Getty Conservation Institute: Los Angeles, USA.
292. Dickie, M.W. 1996. "What Is a Kolossos and How Were Kolossoi Made in the Hellenistic Period?" *Greek, Roman, and Byzantine Studies* 37(3): 237–257.
293. Mattusch, C.C. 2008. "Metalworking and Tools." In *The Oxford Handbook of Engineering and Technology in the Classical World*, ed. J.P. Oleson, 418–438. Oxford University Press: Oxford.
294. Furtwängler, A. and K. Reichhold. 1910. *Griechische Vasenmalerei III*. F. Bruckmann: Munich, Germany.
295. Blumner, H. 1887. *Technologie und Terminologie der Gewerbe und Kunste bei Griechen und Romern*. B.G. Teubner: Leipzig.
296. Gabriel, A. 1932. "La construction, l'attitude et l'emplacement du Colosse de Rhodes." *Bulletin de Correspondance Hellénique* 56: 331–359.
297. Vedder, U. 2006. "A Latin Grand Master, a Greek Philosopher, and the Colossus of Rhodes." In *Proceedings of the XVIth International Congress of Classical Archaeology: Common Ground: Archaeology, Art, Science and Humanities*, ed. C.C. Mattusch, A.A. Donohue, and A. Brauer. Oxbow Books: UK.
298. Mutti, E., G. Orombelli, and R. Pozzi. 1970. "Geological Studies on the Dodecanese Islands (Aegean Sea). IX. Geological map of the Island of Rhodes (Greece). Explanatory notes." *Annales Géologiques des Pays Helléniques* XXII: 77–226.
299. Manoussou-Dellas, K. 2014. *The city of Rhodes in Medieval times: The Transformation of the Fortifications from Late Antiquity to the Fortified City (7th century–1480) (In Greek)*. National Technical University of Athens.

300. Blackman, D.J., P. Knoblauch, and A. Yiannikouri. 1996. "Die Schiffshäuser am Mandrakihafen in Rhodos." *Archäologischer Anzeiger* 3: 371–426.
301. Hoepfner, W.S.E.-L. 1994. *Haus und Stadt im klassischen Griechenland: [Neubearbeitung]*. Deutscher Kunstverl, Munchen.
302. Vedder, U. 2015. *Der Koloss von Rhodos: Archäologie, Herstellung und Rezeptionsgeschichte eines antiken Weltwunders*. NA Nünnerich-Asmus Verlag & Media.
303. Conrad, L.I. 1996. "The Arabs and the Colossus." *Journal of the Royal Asiatic Society* (Third Series) 6: 165–187.
304. Erel, T.L. and F. Adatepe. 2007. "Traces of Historical Earthquakes in the Ancient City Life at the Mediterranean Region. *Journal of Black Sea/ Mediterranean Environment* 13(3): 241–252.
305. Howell, A. et al. 2015. "Late Holocene Uplift of Rhodes, Greece: Evidence for a Large Tsunamigenic Earthquake and the Implications for the Tectonics of the Eastern Hellenic Trench System." *Geophysical Journal International* 203(1): 459–474.
306. Kontogianni, V.A., N. Tsoulos, and S.C. Stiros. 2002. "Coastal Uplift, Earthquakes and Active Faulting of Rhodes Island (Aegean Arc): Modeling Based on Geodetic Inversion." *Marine Geology* 186(3–4): 299–317.
307. Pirazzoli, P.A. et al. 1989. "Crustal Block Movements from Holocene Shorelines: Rhodes Island (Greece)." *Tectonophysics* 170(1–2): 89–114.
308. Radivojević, M. et al. 2010. "On the Origins of Extractive Metallurgy: New Evidence from Europe." *Journal of Archaeological Science* 37(11): 2775–2787.
309. Kassianidou, V. 2013. "Mining Landscapes of Prehistoric Cyprus." *Metalla* 20(2): 5–57.
310. Butterfield, D.A. 2000. "Deep Ocean Hydrothermal Vents." In *Encyclopedia of Volcanoes*, ed. H. Sigurdsson, 857–875. Academic Press: San Diego. 857–875.
311. Greensmith, J.T. 1994. *Southern Cyprus*. Geologists' Association: London.
312. Edwards, S. et al. 2010. *Cyprus*. Classic Geology in Europe. Vol. 7. Terra Publishing: Harpenden, Hertfordshire.
313. Kinnaird, T.C., A.H.F. Robertson, and A. Morris. 2011. "Timing of Uplift of the Troodos Massif (Cyprus) Constrained by Sedimentary and Magnetic Polarity Evidence." *Journal of the Geological Society* 168(2): 457–470.
314. D'Agostino, B. et al. 2016. "Potters, Hippeis and Gods at Penteskouphia (Corinth), Seventh to Sixth Centuries BC." In *The Archaeology of Greece*

and Rome: Studies in Honour of Anthony Snodgrass, Ed. J. Bintliff and N.K. Rutter, 155–182. Edinburgh University Press: Edinburgh.
315. Kassianidou, V. 2000. "Hellenistic and Roman Mining in Cyprus., In *Proceedings of the Acts of the Third International Congress of Cypriot Studies, Nicosia, Cyprus*, ed. V. Karageorghis, R. Laffineur, and F. Vandenabeele, 16–20. A.G. Leventis Foundation: Cyprus.
316. Rostoker, W. 1975. "Some Experiments in Prehistoric Copper Smelting." *Paléorient* 3: 311–315.
317. Craddock, P.T. and M.J. Hughes, eds. 1996. "Furnaces and Smelting Technology in Antiquity." Occasional Paper 48, British Museum: London.
318. Dube, R.K. 2006. "Interrelation between Gold and Tin: A Historical Perspective." *Gold Bulletin* 39(3): 103–113.
319. Berger, D. et al. 2019. "Isotope Systematics and Chemical Composition of Tin Ingots from Mochlos (Crete) and Other Late Bronze Age Sites in the Eastern Mediterranean Sea: An Ultimate Key to Tin provenance?" *PLOS ONE* 14(6): e0218326.
320. Giumlia-Mair, A. and F. Lo Schiavo. 2003. *Le problème de l'étain à l'origine de la métallurgie*. Archaeopress: Oxford.
321. Haynes, D.E.L. 1957. "Philo of Byzantium and the Colossus of Rhodes." *The Journal of Hellenic Studies* 77: 311–312.
322. Hauptmann, A. 2020. "Making Metals: Ancient Metallurgical Processes." In *Archaeometallurgy—Materials Science Aspects*, ed. A. Hauptmann, 295–379. Springer International Publishing: Cham.
323. Ashton, R.H.J. 1986. "Rhodian Bronze Coinage and the Earthquake of 229–226 BC." *The Numismatic Chronicle* (1966–). 146: 1–17.
324. Giardini, D., M.-J. Jimenez, and G. Grunthal. 2003. *European-Mediterranean Seismic Hazard Map*. European Seismological Commission.
325. Lichter, M. et al. 2010. "Sea-Level Changes in the Mediterranean: Past, Present, and Future—A Review." In *Seaweeds and Their Role in Globally Changing Environments*, ed. A. Israel, R. Einav, and J. Seckbach, 3–17. Springer: Dordrecht.
326. Sakellariou, D. and V. Lykousis, eds. 2010. *IGCP 521—INQUA 501 Field Trip Guide*. Avalon Institute of Applied Science: Winnipeg, Canada.
327. Stiros, S.C. and D.J. Blackman. 2014. "Seismic Coastal Uplift and Subsidence in Rhodes Island, Aegean Arc: Evidence from an Uplifted Ancient Harbour." *Tectonophysics* 611: 114–120.
328. Pulak, C. 1998. "The Uluburun Shipwreck: An Overview." *International Journal of Nautical Archaeology* 27(3): 188–224.

329. Bass, G.F. 1987. "Splendors of the Bronze Age." *National Geographic Magazine* 172(6): 692–733.
330. Cline, E.H. and A. Yasur-Landau. 2007. "Musings from a Distant Shore: The Nature and Destination of the Uluburun Ship and Its Cargo." *Tel Aviv* 2007(2): 125–141.
331. Mattern, S.P. 2014. *The Prince of Medicine: Galen in the Roman Empire*. Oxford University Press: Oxford.
332. Walsh, J. 1927. "Galen Visits the Dead Sea and the Copper Mines of Cyprus (166 AD)." *Geographical Society of Philadelphia Bulletin* 25: 92–110.
333. Cooper, J.P. 2009. "Egypt's Nile-Red Sea Canals: Chronology, Location, Seasonality and Function." In *Connected Hinterlands*, ed. L. Blue et al., 195–209. Archaeopress: Oxford, UK.
334. Flaux, C. et al. 2021. "The Late Holocene Record of Lake Mareotis, Nile Delta, Egypt." *E&G Quaternary Science Journal* 70(1): 93–104.
335. Clayton, P.A. 1988. The Pharos at Alexandria." In *The Seven Wonders of the Ancient World*, ed. P.A. Clayton and M. Price, 138–154. Routledge: London.
336. Stanley, J. et al. 2007. "Alexandria, Egypt, before Alexander the Great: A Multidisciplinary Approach Yields Rich Discoveries." *GSA Today* 17(8): 4–10.
337. Bintliff, J.L. et al. 1990. "Trace Metal Accumulation in Soils On and Around Ancient Settlements in Greece." In *Man's Role in the Shaping of the Eastern Mediterranean Landscape*, ed. S. Bottema, G. Entjes-Nieborg, and V. Zeist, 159–172. Balkema: Rotterdam.
338. Worthington, I. 2016. *Ptolemy I: King and Pharaoh of Egypt*. Oxford University Press: Oxford.
339. Trethewey, K. 2018. *Ancient Lighthouses: And Other Lighted Aids to Navigation*. JAZZ-FUSION Books: Torpoint, UK.
340. Hairy, I. 2007. "Pharos, l'Egypte et Platon." In *Images et modernité hellénistiques*, ed. F.-H. Massa-Pairault and G. Sauron, 1000–1029. École française de Rome.
341. Meeus, A. 2015. "The Career of Sostratos of Knidos: Politics, Diplomacy and the Alexandrian Building Programme in the Early Hellenistic Period." In *Greece, Macedon and Persia: Studies in Social, Political and Military History in Honour of Waldemar Heckel*, ed. E. Garvin, T. Howe, and G. Wrightson, 143–171. Oxbow Books: Oxford, UK.
342. Marriner, N., J.P. Goiran, and C. Morhange. 2008. "Alexander the Great's Tombolos at Tyre and Alexandria, Eastern Mediterranean." *Geomorphology* 100(3–4): 377–400.

343. McKenzie, J. 2007. *The Architecture of Alexandria and Egypt, c. 300 B.C. to A.D. 700.* Yale University Press: New Haven, Ct.
344. Flaux, C. et al. 2017. "Geoarchaeology of Portus Mareoticus: Ancient Alexandria's Lake Harbour (Nile Delta, Egypt)." *Journal of Archaeological Science: Reports* 13: 669–681.
345. de Camp, L.S. 1965. "The 'Darkhouse' of Alexandria." *Technology and Culture* 6(3): 423–427.
346. Behrens-Abouseif, D. 2006. "The Islamic History of the Lighthouse of Alexandria." *Muqarnas* 23: 1–14.
347. Hairy, I. 2006. "Le phare d'Alexandrie, concentré de géométrie. *La Recherche* (394): 44–50.
348. Hairy, I. 2020. "The Qaitbay Underwater Site at Alexandria, Egypt: The Evolution of Surveying Techniques." In *Under the Mediterranean: The Honor Frost Foundation Conference on Mediterranean Maritime Archaeology*, ed. S. Demesticha and L. Blue. Honor Frost Foundation: UK.
349. Akarish, A.I. and D. Dessandier. 2011. "Characterization and Source of Sedimentary Rocks of the Alexandria Lighthouse Archaeological Objects, Egypt." *Journal of Applied Sciences* 11: 2513–2524.
350. Dumont, H.J. 2010. *The Nile: Origin, Environments, Limnology and Human Use*. Springer: Berlin.
351. Woodward, J.C. et al. 2008. "The Nile: Evolution, Quaternary River Environments and Material Fluxes." In *Large Rivers*, ed. A. Gupta, 261–292. John Wiley & Sons, Ltd.: Chichester, UK.
352. Hsü, K.J. et al. 1977. "History of the Mediterranean Salinity Crisis." *Nature* 267(5610): 399–403.
353. Ryan, W.B.F. 2009. "Decoding the Mediterranean Salinity Crisis." *Sedimentology* 56(1): 95–136.
354. Garcia-Castellanos, D. et al. 2009. "Catastrophic Flood of the Mediterranean after the Messinian Salinity Crisis." *Nature* 462(7274): 778–781.
355. Brierley, C., K. Manning, and M. Maslin, 2018. "Pastoralism May Have Delayed the End of the Green Sahara." *Nature Communications* 9(1): 4018.
356. Stanley, J.-D. et al., 2003. "Nile Flow Failure at the End of the Old Kingdom, Egypt: Strontium Isotopic and Petrologic Evidence." *Geoarchaeology* 18(3): 395–402.
357. Touzeau, A. et al. 2013. "Egyptian Mummies Record Increasing Aridity in the Nile Valley from 5500 to 1500 Yr before present." *Earth and Planetary Science Letters* 375(0): 92–100.

358. Manning, J.G. et al. 2017. "Volcanic Suppression of Nile Summer Flooding Triggers Revolt and Constrains Interstate Conflict in Ancient Egypt." *Nature Communications* 8(1): 900.
359. Stanley, D.J. and A.G. Warne. 1993. "Sea Level and Initiation of Predynastic Culture in the Nile Delta." *Nature* 363(6428): 435–438.
360. El-Asmar, H.M. and P. Wood. 2000. "Quaternary Shoreline Development: The Northwestern Coast of Egypt." *Quaternary Science Reviews* 19(11): 1137–1149.
361. Wali, A.M.A., M.E. Brookfield, and B.C. Schreiber. 1994. "The Depositional and Diagenetic Evolution of the Coastal Ridges of Northwestern Egypt." *Sedimentary Geology* 90(1–2): 113–136.
362. Embabi, N.S. 2018. "Ridge-Depression Landscape Along the Mediterranean NW Coast of the Western Desert." In *Landscapes and Landforms of Egypt: Landforms and Evolution*, ed. N.S. Embabi, 263–278. Springer International Publishing: Cham.
363. Lisiecki, L.E. and M.E. Raymo. 2005. "A Pliocene-Pleistocene Stack of 57 Globally Distributed benthic δ18O Records." *Paleoceanography* 20(1): PA1003.
364. Gamal, M.A. 2013. "Truthfulness of the Existence of the Pelusium Megashear Fault System, East of Cairo, Egypt." *International Journal of Geosciences* 4(01): 212–227.
365. Neev, D. 1977. "The Pelusium Line—a Major Transcontinental Shear." *Tectonophysics* 38(3): T1–T8.
366. Goiran, J.-P. et al. 2018. "Relative Sea Level Variations at Alexandria (Nile Delta, Egypt) over the Last Millennia: Archaeological Implications for the Ancient Harbour." *Ägypten und Levante* 28: 219–234.
367. Stanley, J.-D. 2005. "Submergence and Burial of Ancient Coastal Sites on the Subsiding Nile Delta Margin, Egypt." *Méditerranée* 104: 65–73.
368. Goiran, J.-P. et al. 2005. "Évolution géomorphologique de la façade maritime d'Alexandrie (Égypte) au cours des six derniers millénaires." *Méditerranée* 104: 61–64.
369. Shaw, B. et al. 2008. "Eastern Mediterranean Tectonics and Tsunami Hazard Inferred from the AD 365 Earthquake." *Nature Geoscience* 1(4): 268–276.
370. Polonia, A., S.C. Vaiani, and G.J. de Lange. 2016. "Did the A.D. 365 Crete Earthquake/Tsunami Trigger Synchronous Giant Turbidity Currents in the Mediterranean Sea?" *Geology* 44(3): 191–194.
371. Nur, A. 2010. "Destructive Earthquakes in Alexandria and Aboukir Bay?" In *Alexandria and the North-Western Delta*, ed. D. Robinson

and A. Wilson, 127–137. Oxford Centre for Maritime Archeology: Oxford, UK.

372. Goiran, J.-P. 2012. "Caractérisation d'un dépôt de tsunami dans le port antique d'Alexandrie par l'étude exoscopique des quartz: apports et limites de la méthode." In *Archéosismicité & tsunamis en Méditerranée*, ed. I. Rebe-Marichal, A. Laurenti, I. Boehm, and J.-P. Goiran, 157–190. Groupe APS: France.
373. Hamouda, A. 2010. "Worst Scenarios of Tsunami Effects along the Mediterranean Coast of Egypt." *Marine Geophysical Research* 31(3): 197–214.
374. Gibb, H.A.R. 1929. *Ibn Battúta: Travels in Asia and Africa, 1325–1354*. R.M. McBride & Co.: New York.
375. Rosen, W. 2014. *The Third Horseman: Climate Change and the Great Famine of the 14th Century*. Viking: New York.
376. Schmid, B.V. et al. 2015. "Climate-Driven Introduction of the Black Death and Successive Plague Reintroductions into Europe." *Proceedings of the National Academy of Sciences* 112(10): 3020–3025.
377. Abdel-Hamid, S.Z. 1958. *Kitab al-istibsar fi aja'ib al-amsar: Description de la Mekke et de Médine de l'Egypte et de l'Afrique septentrionale*. Université d'Alexandrie: Alexandria, Egypt.
378. Panckoucke, C.L.F. and É. Geoffroy-Saint-Hilaire. 1809. *Description de l'Égypte ou Recueil des observations et des recherches qui ont été faites en Égypte pendant l'expédition de l'armée française*. Paris.
379. Ga, E. 2018. *Square Octagon Circle*. Siglio: New York.
380. Klein, H.A. 2012. *The Science of Measurement: A Historical Survey*. Dover Publications: Garden City, NY.
381. Lewis, M.J.T. 2009. *Surveying Instruments of Greece and Rome*. Cambridge University Press: Cambridge.
382. McConnell, J.R. et al. 2020. "Extreme Climate after Massive Eruption of Alaska's Okmok Volcano in 43 BCE and Effects on the Late Roman Republic and Ptolemaic Kingdom." *Proceedings of the National Academy of Sciences* 117(27): 15443–15449.
383. Syvitski, J.P.M. et al. 2009. "Sinking Deltas Due to Human Activities." *Nature Geoscience* 2(10): 681–686.
384. Stanley, D.J. and A.G. Warne. 1998. "Nile Delta in Its Destruction Phase." *Journal of Coastal Research* 14(3): 795–825.
385. Church, J.A. et al. 2008. "Understanding Global Sea Levels: Past, Present and Future." *Sustainability Science* 3(1): 9–22.
386. Bohannon, J. 2010. "The Nile Delta's Sinking Future." *Science* 327(5972): 1444–1447.

387. Kelly, G. 2004. "Ammianus and the Great Tsunami." *The Journal of Roman Studies* 94: 141–167.
388. Brand, S. 2008. *Clock of the Long Now: Time and Responsibility: the Ideas Behind the World's Slowest Computer: Time and Responsibility: The Ideas Behind the World's Slowest Computer*. Basic Books.
389. Li, X. et al. 2021. "Ultrawhite $BaSO_4$ Paints and Films for Remarkable Daytime Subambient Radiative Cooling." *ACS Applied Materials & Interfaces* 13(18): 21733–21739.